Wolf-Rayet Stars
W.-R. Hamann, A. Sander, H. Todt, eds.
Potsdam: Univ.-Verlag, 2015
URL: http://nbn-resolving.de/urn:nbn:de:kobv:517-opus4-84268

Detection and Characterization of Wolf-Rayet stars in M81 with GTC/OSIRIS spectra and HST images

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Here we investigate a sample of young star clusters (YSCs) and other regions of recent star formation with Wolf-Rayet (W-R) features detected in the relatively nearby spiral galaxy M81 by analysing long-slit (LS) and Multi-Object Spectroscopy (MOS) spectra obtained with the OSIRIS instrument at the 10.4-m Gran Telescopio Canarias (GTC). We take advantage of the synergy between GTC spectra and Hubble Space Telescope (HST) images to also reveal their spatial localization and the environments hosting these stars. We finally discuss and comment on the next steps of our study.

1 Introduction

W-R stars, the short-lived descendants of massive O-type stars at their last stages of evolution, are expected to have an important influence on the energetics, dynamics and chemical evolution of the interstellar medium over the lifetime of galaxies (Hillier 2000). Hence the importance of their study in different galaxies and environments. Even though their mere detection reveals recent burst of high-mass star formation in galaxies (Schaerer & Vacca 1998).

Here we report and characterize an initial sample of YSCs and other regions where we detected W-R features in their spectra: like the strong and broad emission lines of He II, N and C. These were discovered in the disk of the relatively nearby spiral galaxy M81 (3.63 Mpc, m-M = 27.8; Freedman et al. (1994)). W-R features were found by analysing LS and MOS spectra obtained by using the OSIRIS instrument at the 10.4-m GTC in three different seasons of observation. We performed a very detailed multiple Gaussian fitting of the nebular and broad emission lines within the so called W-R bumps to classify these objects into the Nitrogen (WN) or Carbon (WC) sequence, and early (E) or late (L) subtypes, and also to obtain some of their most important parameters: like their typical luminosities, EWs and magnitudes (paper in prep.). Additionally, the use of HST images reveals their spatial localization as well as their environments. The detection of W-R features immediately places strong constraints on several parameters, like the age of the most recent starburst episodes.

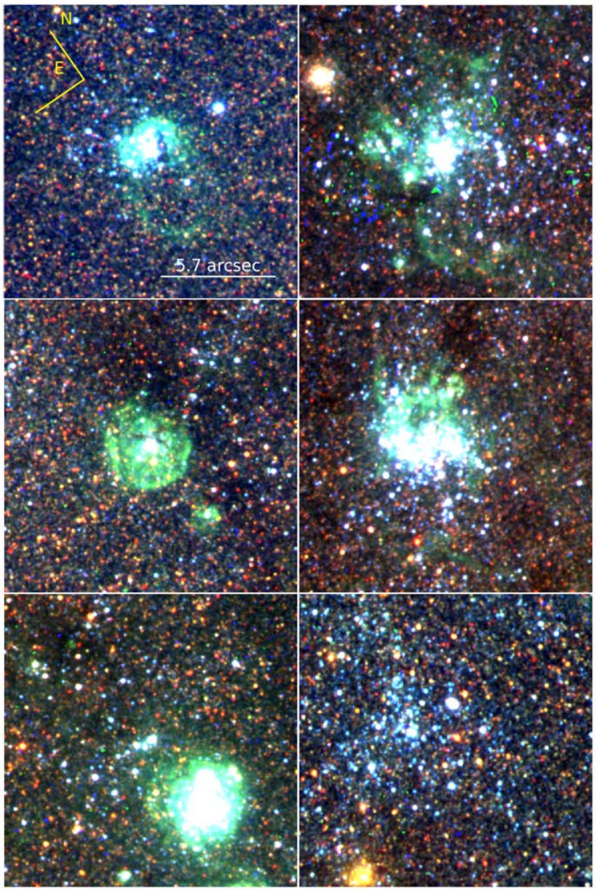

Fig. 1: A representative sample of 6 of the 14 YSCs and other regions hosting the W-R features in M81. The color stamps were formed by combining: B, V and I HST filters. W-R stars are located at the center of each image which it is not necessarily the center of the cluster. Note the ionized gas in form of bubbles and shells extending at least tens to hundreds of pc surrounding some of these objects and presenting a rich diversity of morphologies but also "isolated" with absence of ionized gas around. The orientation and a scale of 5.7 arcsec (100 pc) are also shown for reference.

2 Observations

GTC/OSIRIS observations on M81 W-R stars as well as the HST images used in our study, are briefly presented in this section.

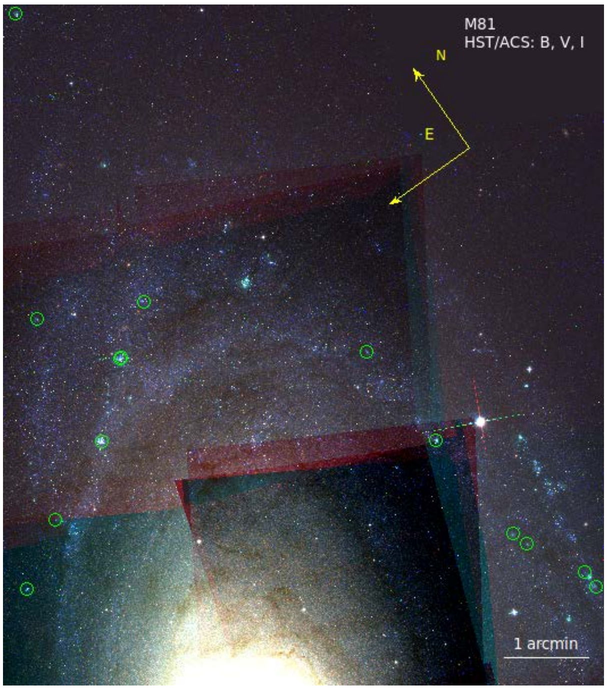

Fig. 2: An image of a section of M81 formed by combining: B, V and I HST filters, showing the spatial locations of the W-R stars detected (green circles). It can be seen that these were discovered in the disk, mostly in the spiral arms of the galaxy. The orientation and a scale of 1 arcmin are also shown for reference.

2.1 Spectroscopy: GTC/OSIRIS

Spectroscopic observations were carried out with the OSIRIS instrument at the 10.4-m GTC in three different seasons of observation with both the LS and MOS. Observations included bias, flat fields, calibration lamps and standard stars. Slits of width 1.2 arcsec, a spatial scale of 0.254 arcsec/pix, the spectra cover a range from 3700 to 7500 Å, with a spectral resolution around 7 Å, and a seeing of around 0.7-1 arcsec. Data reduction were carried out in the standard manner by using the tasks available in the IRAF software package. Fig. 3. shows an example for WR1.

2.2 HST images

We use HST images of M81 publicly available in three different filters: B (F435W), V (F606W) and I (F814W) (PI: Andreas Zesas). With a sampling of 0.05 arcsec/pix which at the distance to M81 it corresponds to 0.88 pc/pix. The spatial resolution in these images, measured as the Full Width at Half Maximum (FWHM) of the Point Spread Function (PSF) is 2.1 pixel (1.8 pc).

The use of HST images reveals the spatial localization of the YSCs, associations and other regions hosting the W-R stars as well as their environments, located in the disk, mostly in the spiral arms of the M81 (see Fig. 2). Shells and ring nebulae have been observed for a subset of W-R stars in M81 exhibiting a variety of morphologies and sizes. These are believed to represent material ejected during the red supergiant (RSG) or luminous blue variable (LBV) phases that is photo-ionized by the W-R stars (Crowther 2007).

3 Analysis and Discussion

Because of the quality of our spectra, we have adopted the approach of Brinchmann et al. (2008) to estimate the bump luminosity of the W-R stars. We calculate the excess flux above the best-continuum in regions around the main W-R features, for each feature we fit the relevant nebular emission lines jointly with multiple Gaussian for each bump which can be expected to be present. Fig. 4. shows an example for WR1. Visual spectral classification of W-R stars is based on emission line strengths and line rations following Smith (1968). WN spectral subtypes follow a scheme involving line ratios of N III-V and He I-II, ranging from WNE to WNL. WC spectral subtypes depend on the line ratios of C III and C IV lines ranging from WCE to WCL (Crowther 2007).

We detected 14 W-R stars in M81 by combining GTC spectra with HST images. All objects present WN features, mostly late type (WNL), 6 of these present additional WC features, early type (WCE). Observed luminosities of He II λ 4686, C IV λ 5808 broad lines are more in agreement with those found in the Milky Way for single WR stars than in the LMC. This is consistent with the near to solar metallicity of M81. The obtained important parameters: like their typical luminosities, EWs and magnitudes will be reported in a coming paper (in prep.)

This work was supported by CONACyT (Mexico) research grant.

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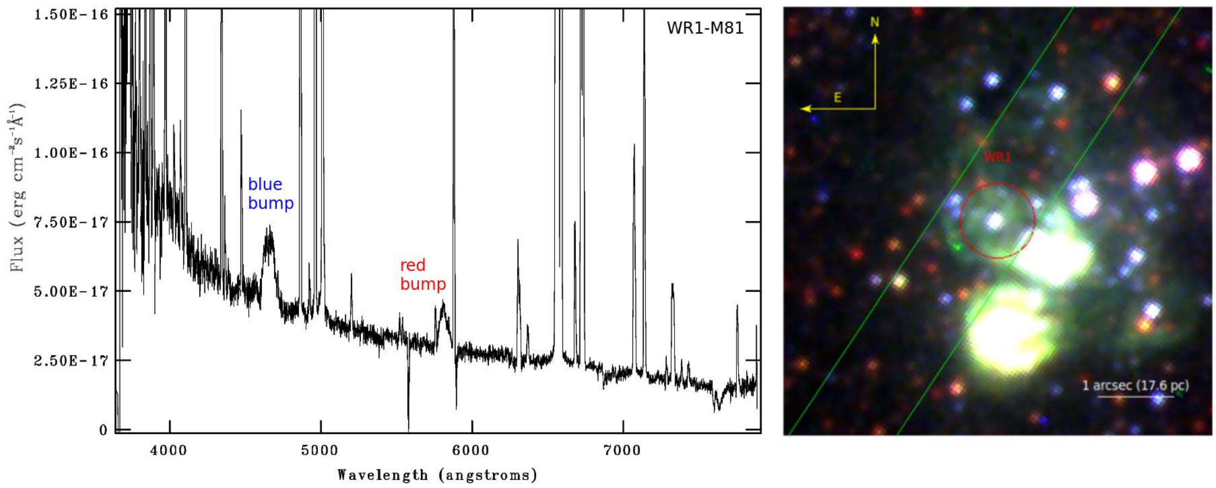

Fig. 3: (Left) An extracted spectrum of WR1, discovered with GTC/OSIRIS long-slit data. As can be seen, it presents strong and broad emission lines, due to their powerful stellar winds, instead of the narrow absorption lines that are typical of normal stellar populations (Crowther 2007); (Right) Thanks to the great spatial resolution of the HST images we can appreciate the environment surrounding the W-R stars in great detail: WR1 (red circle) is located in a rich star cluster complex, not in the center of it, and presenting several bubbles of ionized gas, whose spectra are also separately detected in the ccd. At 1 arcsec to the West there is F04B16353, this is a blue stellar cluster previously reported in the catalogue of Santiago-Cortés et al. (2010). WR1 was has the highest galactocentric radius of the sample. The slit-width (green rectangle) is 1.2 arcsec. A scale of 1 arcsec (17.6 pc) is also shown for reference. North is up, East to the left.

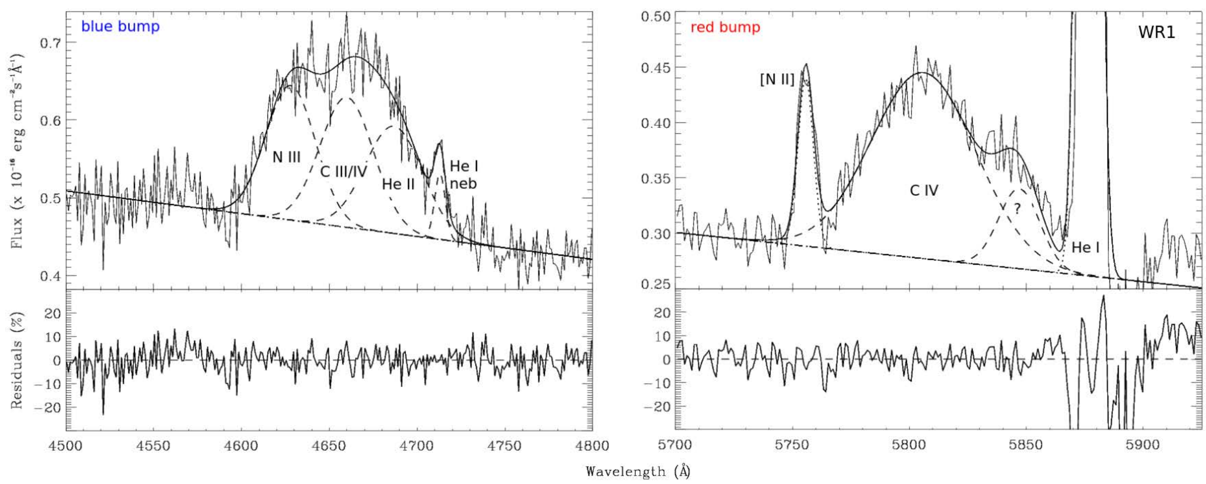

Fig. 4: An illustration of the method followed to classify the W-R stars and to determine some of their most important parameters. We applied a very detailed multiple Gaussian fitting of the nebular and broad emission lines within the so called W-R bumps. Detected emission lines for WR1 were: He II λ 4686, N III λ 4640, CIV λ 5803-08. Nebular emission lines: [He I/Ar IV] λ 4711-13, [N II] λ 5755, He I λ 5676. Detection of He II and N III λ 4640 indicates WNL, there is not detection of N IV neither N V which would indicate WNE. Detection of CIV indicates WCE, there is not detection of C III 5696 which would indicate WCL. The total of the fitted lines are shown by the continuous line, the residuals are also shown.

Paul Crowther: 1) I would recommend using template spectra of WR stars (e.g. Crowther & Hadfield) rather than simple gaussian fittings. 2) Future progress with searches beyond the local group requires large format IFUs (e.g. MUSE).

Víctor Gómez-González: Thank you for your comments. Yes, we will try the WR templates that you recommend and then we can compare with the results obtained by applying the multiple gaussians fittings approach.

Jose Groh: There is an interesting core-collapse SN in M81 (SN 1993 J, IIb). Since the progenitor of this SN seems to have an initial mass similar to the WRs you have detected, it may be interesting to compare the location of this SN with the WR star forming regions that you have detected. This comparison may provide constraints on the massive star population around these WRs.

Claus Leitherer: Some of the stars/clusters are surrounded by gas. Do you see any evidence of narrow, nebular He II 4686 emission?

Víctor Gómez-González: Yes, the majority of our objects with WR features are surrounded by gas and we do see the narrow nebular He II 4686 emission line in some of them, even in some other regions without WR features.