Photometric and spectroscopic studies of star-forming regions within Wolf–Rayet galaxies

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ABSTRACT
We present a study of the properties of star-forming regions within a sample of seven Wolf–Rayet (WR) galaxies. We analyse their morphologies, colours, star-formation rates (SFRs), metallicities and stellar populations, combining broad-band and narrow-band photometry with low-resolution optical spectroscopy. The UBVRI observations were made with the 2-m HCT (Himalayan Chandra Telescope) and 1-m ARIES telescope. The spectroscopic data were obtained using the Hanle Faint Object Spectrograph Camera (HFOSC) mounted on the 2-m HCT. The observed galaxies are NGC 1140, IRAS 07164+5301, NGC 3738, UM 311, NGC 6764, NGC 4861 and NGC 3003. The optical spectra were used to search for the faint WR features, to confirm that the ionization of the gas is caused by the massive stars, and to quantify the oxygen abundance of each galaxy using several independent empirical calibrations. We detected broad features originating in WR stars in NGC 1140 and 4861 and used them to derive the massive star populations. For these two galaxies we also derived the oxygen abundance using a direct estimation of the electron temperature of the ionized gas. The N/O ratio in NGC 4861 is ~0.25–0.35 dex higher than expected, which may be a consequence of the chemical pollution by N-rich material released by WR stars. Using our Hα images we identified tens of star-forming regions within these galaxies, for which we derived the SFR. Our Hα-based SFR usually agrees with the SFR computed using the far-infrared and the radio-continuum flux. For all regions we found that the most recent star-formation event is 3–6 Myr old. We used the optical broad-band colours in combination with Starburst99 models to estimate the internal reddening and the age of the dominant underlying stellar population within all these regions. Knots in NGC 3738, 6764 and 3003 generally show the presence of an important old (400–1000 Myr) stellar population. However, the optical colours are not able to detect stars older than 20–50 Myr in the knots of the other four galaxies. This fact suggests that both the current intensity of the starbursts and the star-formation activity have been ongoing for at least a few tens of millions of years in these objects.

Key words: stars: Wolf–Rayet – galaxies: abundances – galaxies: photometry – galaxies: starburst – galaxies: stellar populations.

1 INTRODUCTION
Wolf–Rayet (WR) galaxies are defined as those galaxies that show broad emission features associated with WR stars in their integrated spectra. The presence of the WR stars is reflected in galaxy spectra as two important broad features, the blue WR bump (between 4650 and 4690 Å, mainly owing to N III, N V and He II) and the red WR bump (at ~5808 Å, owing to the C IV emission line). The nebular He II λ4686 line is also associated with the presence of these massive stars. However, other ionization mechanisms may also create this line, as discussed by Garnett et al. (1991), Garnett (2004), Guseva,
Izotov & Thuan (2000) and López-Sánchez & Esteban (2010a). WR galaxies were first catalogued by Conti (1991) and later by Schaerer, Contini & Pindao (1999), but hundreds of these objects were found using the Sloan Digital Sky Survey (SDSS) (Zhang et al. 2007; Brinchmann, Kunth & Durrell 2008).

The morphological type of WR galaxies varies from low-mass blue compact dwarf (BCD) irregular galaxies to massive spirals and luminous merging galaxies. WR features are often found in starburst galaxies. The progenitors of the WR stars are the most massive (M \gtrsim 25M_☉) luminous (10^5 to 10^6L_☉) and hot (~50 000 K) O stars, and they end their days by exploding as Type II/IC supernovae (Meynet & Maeder 2005). In fact, the minimum stellar mass that an O star needs to reach the WR phase, and its duration, depends on the metallicity. In general, the WR phenomenon is short-lived, existing for only \lesssim 1 Myr.

Hence, the detection of WR features in the spectra of a galaxy constrains the properties of the star-formation processes. Because the first WR stars typically appear around 2–3 Myr after the starburst is initiated and disappear within some 5 Myr (Meynet & Maeder 2005), their detection provides information about both the age and the strength of the burst, offering the opportunity to study an approximately coeval sample of very young starbursts (Schaerer & Vacca 1998) and the role played by the interaction with or between dwarf galaxies and/or low-surface-brightness objects in the triggering mechanism of the strong star-formation activity (López-Sánchez & Esteban 2008; López-Sánchez & Esteban 2010). Furthermore, the detection of WR stars also allows the study of the formation and feedback of massive stars in starburst galaxies (Guseva et al. 2000; Fernandes et al. 2004; López-Sánchez, Esteban & Rodríguez 2004a; Buckalew, Kobulnicky & Dufour 2005; López-Sánchez & Esteban 2010a, b).

With the aim of gaining a better understanding of the properties of WR galaxies, we performed a detailed analysis of a sample of these objects using broad-band U, B, V, R, I, narrow-band Hα imaging and low-resolution optical spectroscopy. In this paper we present the results of seven of our analysed WR galaxies. The main properties of these objects are given in Table 1.

The paper is organized as follows. Observations and data reduction are described in Section 2. The broad-band and narrow-band photometric results are presented in Section 3. This section includes the identification of the star-forming regions, the determination of their optical colours, and the estimation of both the star-formation rate and the most recent star-forming episode via the analysis of the net-Hα images. Section 4 describes our results from optical spectroscopy. There we analyse the physical conditions of the ionized gas (reddening, nature of the ionization, electron density and electron temperature when possible) and compute the oxygen abundances of the ionized gas within our sample galaxies. Section 4 also includes an analysis of the WR features in NGC 1140 and 4861. We discuss our results in Section 5, where we first describe how we determined the ages of both the old and the young stellar populations. We also present the analysis of the individual galaxies in Section 5. Finally, we peresent our summary and conclusions in Section 6.

## 2 OBSERVATIONS AND DATA REDUCTION

Except for NGC 1140, broadband (UBVRI) and spectroscopic observations of the star-forming knots within our WR galaxy sample were obtained with the HFOSC (Hanle Faint Object Spectrograph Camera) mounted on the 2-m Himalayan Chandra Telescope (HCT) of the Indian Astronomical Observatory (IAO). HFOSC is equipped with a 2k × 4k Sité CCD chip. The central 2k × 2k region, with a plate scale of 0.296 arcsec pixel^{-1}, provides a 10 arcmin × 10 arcmin field of view.

Broad-band photometric observations of NGC 1140 were obtained in the UBVRI bands using the ARIES 1-m telescope with a 2k × 2k CCD. The plate scale is 0.37 arcsec pixel^{-1}, providing an area of 12.6 arcmin × 12.6 arcmin. Observations were performed under photometric sky conditions. In order to improve the signal-to-noise ratio (S/N), a 2 × 2 binning mode was used on the chip. In addition to the galaxy frames, the typical calibration frames (for example bias and flats) were used to process the science frames. Photometric standard stars from the list compiled by Landolt (1992) were observed for photometric calibration.

Spectroscopic observations of the galaxies were obtained with a combination of slit 1671 (slit width 1.92 arcsec × 11 arcmin) and grism 7, covering the wavelength range 3500–7500 Å. This slit and grism combination gives a dispersion of 1.5 Å pixel^{-1} and a spectral resolution of ~11 Å. As we used the HFOSC instrument at the 2-m HCT for the majority of our spectroscopic observations, the spatial scale is 0.296 arcsec pixel^{-1}. In the case of our observations of NGC 1140, the spatial scale is 0.37 arcsec pixel^{-1}. The star-forming regions were identified using short exposures through the Hα filter and then were centred through the slit. The position of the slit used in each case is marked in Figs 1–7. The typical seeing was between 1.0 and 1.5 arcsec. Because of the low air-mass at which the

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**Table 1.** List of Wolf–Rayet galaxies observed in our study.a

| Object name     | NGC 1140 | IRAS 07164+5301d | NGC 3738 | UM 311 | NGC 6764 | NGC 4861 | NGC 3003 |
|-----------------|----------|-----------------|----------|--------|----------|----------|----------|
| RA [J2000]      | 02 54 33 | 07 20 25        | 11 35 49 | 01 15 34 | 19 08 16 | 12 59 02 | 09 48 36 |
| Dec [J2000]     | -10 01 40 | +52 55 32      | +54 31 26 | -00 51 46 | +50 56 00 | +34 51 34 | +33 25 17 |
| mV [mag]        | 12.8     | 14.13           | 12.13    | 17.9    | 12.56    | 12.9     | 12.33    |
| V_{e} [km s\(^{-1}\)] | 1501     | 12981           | 229     | 1675   | 2416     | 833      | 1478     |
| Distance\(^{c}\) [Mpc] | 17.90    | 177             | 5.56    | 18.7   | 31.3     | 14.8     | 24.00    |
| E(B−V)\(_{\text{Galactic}}\) [mag] | 0.038 | 0.075            | 0.010   | 0.039   | 0.067    | 0.010    | 0.013    |
| M\(_{V}\) [mag]  | -18.43   | -22.03          | -16.59  | -13.42 | -19.85   | -17.94   | -19.56   |
| Z\(_{b}\)       | 0.010    | 0.014           | 0.0089  | 0.0074 | 0.0195   | 0.0033   | 0.016    |
| 1.2 arcmin\(^{d}\) [kpc] | 6.1      | 61.0            | 1.9     | 6.4     | 10.6     | 5.1      | 8.16     |

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**Notes:**

a Data taken from NASA/Extragalactic Database (NED).

b Z = 0.02 × 10^{log(O/H)−log(O/H)⊙}, assuming 12 + log(O/H)⊙ = 8.66, Asplund et al. (2005).

c Foreground extinction from Schlegel et al. (1998).

d Parameters derived in this work.

Projective distance, in kiloparsecs, of 1.2 arcmin at the distance of the galaxy.

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**References:**

- Izotov & Thuan (2000)
- López-Sánchez & Esteban (2010a)
- Schaerer, Contini & Pindao (1999)
- Schlegel, Finkbeiner & Davis (1998)
- Meynet & Maeder (2005)
- López-Sánchez & Esteban (2008)
- Meynet & Maeder (2004a)
- Guseva et al. (2000)
- Fernandes et al. (2004)
- Buckalew, Kobulnicky & Dufour (2005)
- López-Sánchez & Esteban (2010a, b)
galaxies were usually observed ($m_X$ between 1.0 and 1.4), we should not expect problems arising from differential refraction. However, we did use the parallactic angle in the case of our observations of UM 311, because this galaxy was observed at an air-mass of $m_X = 2.2$. Spectrophotometric standard star were observed in order to obtain the flux calibration of the spectrum. In this case we used the same grism 7 but the broad slit 1340 (15.41 arcsec $\times$ 11 arcmin).

A log of our observations is given in Table 2.

All preprocessing and data reduction was performed in the standard manner using various tasks available with the Image Reduction and Analysis Facility (IRAF\(^1\)). The Munich Image Data Analysis System (MIDAS) software was used for identification and removal of

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\(^1\)\text{IRAF} is distributed by NOAO, which is operated by AURA Inc., under cooperative agreement with NSF.
cosmic ray events from the science frames. All images were bias-subtracted and flat-fielded using master bias and normalized master flats. Dark frames were not needed in any case. Multiple frames of the galaxies taken using different filters were aligned and co-added in a final frame.

Narrow-band Hα line images were obtained following the standard procedure described by Waller (1990). The R-band image was used for continuum subtraction. Spectrophotometric standard stars chosen from Oke (1990) were observed to calibrate the Hα images. A scale factor between the Hα and R-band images was determined using the non-saturated field stars in the galaxy field, after accounting for the difference in the full width at half-maximum (FWHM) of the stellar profile. The R-band continuum image was scaled to the Hα image and subtracted from the Hα image to obtain the Hα line image of the galaxy. We then defined apertures to cover all the flux coming from different knots throughout each galaxy. A nearby emission-free region was always considered in order to estimate the surrounding background. The Hα fluxes of the knots were then flux-calibrated using the results provided by the standard stars.

The spectroscopic data analysis was also performed using standard routines of the IRAF software. For each two-dimensional spectrum we extracted a one-dimensional spectrum integrating a particular region along the spatial direction, usually centring on the brightest point of the galaxy. We carefully checked that the one-dimensional spectrum obtained for each object had the optimal S/N; that is, that the emission lines were not diluted by the stellar continuum and that the S/N was high. Each one-dimensional spectrum was then wavelength-calibrated using a FeAr arc spectrum. The absolute flux calibration of the spectra was achieved by observing spectrophotometric standard stars chosen from Oke (1990). We also used IRAF to correct the spectra for foreground extinction using the Galactic E(B − V) values listed in Table 1 and extracted from Schlegel, Finkbeiner & Davis (1998).

3 Photometry Results

The R-band and the continuum-subtracted Hα images of all galaxies are shown in Figs 1–7. We used the continuum-subtracted Hα images to identify the star-forming regions (knots) within each galaxy. The knots were identified by visual inspection. However, a threshold of 4–5 times sigma of background was taken to delimit the size of each knot. We always consider circular apertures. The diameter of the regions (in arcsec) and their corresponding physical size (in kpc) are given in Table 3. The corresponding identification number for each star-forming region is included in Figs 1–7.

3.1 Broad-band photometry

Aperture photometry of the star-forming regions was carried out within the circular apertures drawn in Figs 1–7. We then computed the apparent V magnitude, mv, and the colours U − B, B − V, V − R and V − I of all regions.

Broad-band colours were corrected for foreground extinction (i.e. Galactic extinction) using the E(B − V) data provided by Schlegel et al. (1998) and listed in Table 1. All derived magnitudes and colours are given in Table 3.

Table 3 does not include a correction for internal extinction. However, for many knots this correction can be determined by a comparison of the broad-band colours with the predictions given by the Starburst99 (Leitherer et al. 1999) evolutionary synthesis models.
models, as will be explained in Section 5.2. In any case, for the majority of the knots the correction for internal extinction seems to be small, even almost zero.

No correction for emission lines from the ionized gas has been considered, although it may be important in some bright, intense, star-forming knots (e.g. Salzer, MacAlpine & Boroson 1989; López-Sánchez & Esteban 2008; Reines et al. 2010), as will be explained in Section 5.2.

Uncertainties quoted in Table 3 consider only the photometric error.

### 3.2 Narrow-band Hα photometry

We used the continuum-subtracted Hα image (see Figs 1–7) to estimate the Hα flux of every star-forming knot within each galaxy. Hα fluxes have been corrected for extinction, assuming

\[ A_{\text{H}\alpha} = 1.758 \times 0.692 E(B - V) = 2.54 E(B - V), \]

following López-Sánchez & Esteban (2008), who considered a Milky Way reddening law with $R_V = 3.1$ following Cardelli, Clayton & Mathis (1989). Here $E(B - V)$ considers both the
foreground and the intrinsic extinction, as listed in Table 1 (Galactic extinction) and Table 9 (internal extinction); that is,
\[ E(B - V) = E(B - V)_{\text{Galactic}} + E(B - V)_{\text{internal}}. \]  
(2)

The measured H\(\alpha\) flux is contaminated by \([\text{N} \text{ ii}]\lambda\lambda 6548, 6583\) emission. The estimation of the \([\text{N} \text{ ii}]\) contribution was derived using the \([\text{N} \text{ ii}]\lambda\lambda 6548, 6583/H\(\alpha\)) ratio derived from our optical spectroscopic data (which is listed in the last column of Table 4) and applying
\[ F_{\text{H\(\alpha\)},\text{corr}} = F_{\text{H\(\alpha\)}} \left(1 + \frac{[\text{N} \text{ ii}]\lambda\lambda 6548, 6583}{H\(\alpha\)}\right)^{-1}. \]  
(3)

where \(F_{\text{H\(\alpha\)},\text{corr}}\) and \(F_{\text{H\(\alpha\)}}\) are, respectively, the corrected and uncorrected H\(\alpha\) flux.

We did not consider the transmittance of the narrow-band filter in the position of the \([\text{N} \text{ ii}]\) lines – as explained in López-Sánchez & Esteban (2008) – because of the relatively large FWHM (≥ 100 Å) of the narrow-band filter used. The corresponding \([\text{N} \text{ ii}]\)/H\(\alpha\) ratio was typically found to be between 0.03 (NGC 4861) and 0.36 (NGC 3003). Except for the case of NGC 6764, we considered that all knots within a galaxy have the same \([\text{N} \text{ ii}]\) contribution as was estimated for the region for which we have spectroscopic data. Knot 2 within NGC 6764 is at the centre of the galaxy, which is a low-ionization nuclear emission-line region (LINER, see Section 4.1), and hence the emission coming from the \([\text{N} \text{ ii}]\) lines is 1.4 times stronger than the emission coming from H\(\alpha\).

The final H\(\alpha\) fluxes, corrected for both the extinction and the \([\text{N} \text{ ii}]\) contribution, derived for each star-forming region are compiled in Table 4.

Using the H\(\alpha\) fluxes and considering the distance to the galaxies listed in Table 1, we derived the total H\(\alpha\) luminosity for the analysed star-forming regions within our WR galaxy sample. The results are also listed in Table 4.

The H\(\alpha\) luminosity can be used as a good tracer of star formation activity in galaxies (e.g. Kennicutt 1998; Calzetti et al. 2007). The radiation from the young stars ionizes the surrounding hydrogen gas, giving rise to H\(\alpha\) emission by recombination. Because the H\(\alpha\) luminosity is proportional to the number of ionizing photons produced by the hot stars (which is also proportional to their birth rate), the star-formation rate (SFR) can be easily derived from the H\(\alpha\) luminosity. Only stars with masses > 10 M\(\odot\) and lifetimes < 20 Myr contribute significantly to the integrated ionizing flux, so the emission lines produce a nearly instantaneous measure of the SFR, independent of the previous star formation history.

We adopted the standard Kennicutt (1998) relationship to derive the SFR from the H\(\alpha\) luminosity. The H\(\alpha\)-based SFR values for the star-forming knots observed in our WR galaxy sample are given in Table 4.

Because the galaxy IRAS 07164+5301 has a larger redshift than the other objects (it has a radial velocity of 12 981 km s\(^{-1}\), which means a redshift of \(z ≈ 0.0433\)), the continuum subtraction did not provide any H\(\alpha\)-net flux (or similar) results with null. In this case, we estimated its H\(\alpha\) luminosity using our spectroscopic data. Considering the size and width of the slit used to obtain the spectrum of this galaxy (1.92 arcsec × 5.2 arcsec, see Table 5) and the corresponding angular size of the galaxy (10 arcsec × 21 arcsec), we estimate that the total H\(\alpha\) flux of the galaxy is ~21 times the extinction-corrected H\(\alpha\) flux we measured using our spectrum. Taking into account the values for Galactic (Table 1) and internal (Table 5) reddening, the H\(\alpha\)/H\(\beta\) ratio (2.79) and the H\(\beta\) flux (1.27 × 10\(^{-14}\) erg s\(^{-1}\) cm\(^{-2}\)), we estimate a total H\(\alpha\) flux of ~1.09 × 10\(^{-12}\) erg s\(^{-1}\) cm\(^{-2}\) for IRAS 07164+5301, which is the value given in Table 4. Hence, its total SFR is SFR\(_{H\alpha} \sim 7.6 \text{ M}_\odot \text{yr}^{-1}\).

The H\(\alpha\) equivalent width, W(H\(\alpha\)), of the star-forming knots was calculated using the expression given by Waller (1990). As will be explained in Section 5.1, we will use W(H\(\alpha\)) to estimate the age of the most recent star-formation event. Both quantities are listed in Table 4 for each region.

We have also quantified the strength of the star-formation activity in each knot by computing their SFR per unit area. Table 4 also lists these values, in units of M\(\odot\) yr\(^{-1}\) kpc\(^{-2}\). Fig. 8 compares the SFR per unit area with the H\(\alpha\) equivalent width derived for each knot. The dotted line at log(SFR/A) = −1.5 is included as a visual aid. Knots located above this line are experiencing a relatively high SFR per unit area, and hence they might be considered as starburst regions (knot 1 in NGC 1140 and 4861, and knots 1 and 3 in NGC 6764) or starburst galaxies (IRAS 07164+5301, UM 311, NGC 3738). Note that knot 2 in NGC 6764 hosts a LINER, as will be discussed in the next section. In the case of NGC 3003 all knots are located well below the dotted line in Fig. 8, suggesting that this is just a normal star-forming galaxy.

4 RESULTS FROM OPTICAL SPECTROSCOPY

The one-dimensional spectra obtained for our WR galaxy sample are plotted in Figs 9 and 10. The prominent lines have been identified and marked. These are emission lines from the hydrogen and helium Balmer series, and forbidden emission lines owing to oxygen, nitrogen and sulphur. These spectra have been corrected for foreground (Galactic) extinction using the corresponding \(E(B - V)\) values extracted from Schlegel et al. (1998) (see Table 1) and by making use of the IRAF deredden task. We then directly analysed these dereddened spectra.

Line intensities and equivalent widths were measured by integrating all the flux in the line between two given limits and over a local continuum estimated by eye. In the cases of line blending (usually in the H\(\alpha\)+[N\(\text{ ii}\)]) region, a multiple Gaussian profile fitting procedure was applied to obtain the line flux of each individual line. We used the standard assumption, namely that I(H\(\beta\)) = 100, to compute the line intensity ratios.

The results obtained for each galaxy are compiled in Table 5. These data have been corrected for both internal reddening and underlying stellar absorption following the method described in López-Sánchez & Esteban (2009). This is an iterative procedure to derive simultaneously the reddening coefficient, c(H\(\beta\)), and the equivalent widths of the absorption in the hydrogen lines, W\(_{\text{abs}}\), to correct the observed line intensities for both effects. The method assumes that W\(_{\text{abs}}\) is the same for all the Balmer lines and uses the relationship given by Mazzarrella & Boronson (1993) to perform the absorption correction,
\[ c(H\beta) = \frac{1}{f(\lambda)} \log \left[ \frac{F(\lambda)}{F(H\beta)} \left(1 + \frac{W_{\text{abs}}}{W_{\text{H}\beta}}\right) \right], \]  
(4)
for each detected hydrogen Balmer line, where \(f(\lambda)\) and \(I(\lambda)\) are the observed and the theoretical fluxes (unaffected by reddening or absorption), W\(_{\text{abs}}\), W\(_{\text{H} \beta}\), and W\(_{H\alpha}\) are the equivalent widths of the underlying stellar absorption, the considered Balmer line and H\(\beta\), respectively, and \(f(\lambda)\) is the reddening curve normalized to H\(\alpha\) using the Cardelli et al. (1989) extinction law. All these values are compiled in Table 5. We always considered the theoretical ratios
Table 4. Hα flux, Hα luminosity (corrected for extinction and [N II] emission), derived star-formation rate (SFR) and SFR per unit area, −W(Hα), and age of the most recent star-formation event for the knots of the Wolf–Rayet galaxies analysed in this work. The final column lists the [N II] λλ6548, 6583/Hα ratio derived for some regions using our optical spectroscopic data and used to correct the narrow-band Hα fluxes for [N II] emission.

| Galaxy Knot ID | Metallicity [Z/Z⊙] | Flux [10⁻¹⁴ erg s⁻¹ cm⁻²] | Luminosity [10⁸ erg s⁻¹] | log SFR [M⊙ yr⁻¹] | log (SFR/Area) [M⊙ yr⁻¹ kpc⁻²] | −W(Hα) [Å] | Age [Myr] | [N II]/Hα |
|----------------|---------------------|--------------------------|--------------------------|-------------------|-------------------------------|-----------|---------|----------|
| NGC 1140       | 0.008               | 204 ± 10                 | 777 ± 38                 | −0.21 ± 0.02      | −0.89 ± 0.02                  | 384 ± 80  | 5.0 ± 0.2 | 0.13     |
| NGC 6764       | 0.02                | 12.0 ± 0.4               | 130 ± 9                  | −0.99 ± 0.03      | −1.08 ± 0.03                  | 150 ± 40  | 6.0 ± 0.1 | 0.32     |
| NGC 4861       | 0.004               | 223 ± 11                 | 583 ± 29                 | −0.33 ± 0.02      | −1.02 ± 0.02                  | 845 ± 150 | 4.6 ± 0.2 | 0.03     |
| NGC 3003       | 0.02                | 0.23 ± 0.02              | 1.58 ± 0.14              | −2.90 ± 0.04      | −2.31 ± 0.04                  | 319 ± 90  | 5.6 ± 0.2 | 0.36     |

The Hα data for IRAS 07164+5301 were derived using the spectroscopic data. See text.

The centre of NGC 6764 (knot 2) is a LINER (see Section 4.1), and hence the emission coming from the [N II] lines is larger (1.4 times) than the emission coming from Hα. See text for details.
Table 5. Dereddened line intensity ratios with respect to \( I(H\beta) = 100 \) for the galaxies analysed in this work. We also compile the \( H\beta \) flux, the size of the extracted area, the reddening coefficient, \( c(H\beta) \), and the equivalent widths of the absorption in the hydrogen lines, \( W_{abs} \), used to correct the spectra for internal reddening, and the equivalent widths of the emission \( H\beta \) Balmer lines.

| Line | \( f(\lambda) \) | NGC 1140 | IRAS 07164+5301 | NGC 3738 | UM 311 | NGC 6764 | NGC 4861 | NGC 3003 |
|------|----------------|---------|----------------|---------|--------|---------|--------|---------|
| [O\textsc{ii}] 3728 | 0.322 | 241 ± 17 | 238 ± 28 | 680 ± 110 | 257 ± 90 | 142 ± 44 | 88.3 ± 5.8 | 209 ± 65 |
| [Ne\textsc{iii}] 3869 | 0.291 | 21.9 ± 3.9 | ... | 41 | ... | ... | 37.0 ± 2.5 | ... |
| [Ne\textsc{iii}] 3969+H7 | 0.267 | 10.2 ± 1.1 | ... | ... | ... | ... | 26.5 ± 2.1 | ... |
| H\alpha 4101 | 0.230 | 26.2 ± 2.1 | ... | 27 | ... | ... | 26.0 ± 1.7 | ... |
| H\gamma 4340 | 0.157 | 47.0 ± 3.1 | ... | 49 ± 13 | 35 ± 11 | 50 ± 14 | 47.2 ± 2.5 | 47 ± 17 |
| [O\textsc{ii}] 4363 | 0.150 | 1.53 ± 0.49 | ... | ... | ... | ... | 9.79 ± 0.77 | ... |
| He\textsc{i} 4471 | 0.116 | 3.63 ± 0.64 | ... | ... | ... | ... | 3.28 ± 0.35 | ... |
| Fe\textsc{ii} 4658 | 0.059 | ... | ... | 0.93 ± 0.26 | ... | ... | ... | ... |
| Broad He\textsc{ii} 4686 | 0.049 | 3.3 ± 1.4 | ... | ... | ... | ... | 2.62 ± 0.78 | ... |
| [Ar\textsc{v}] 4711 | 0.043 | ... | ... | ... | ... | ... | 1.09 ± 0.23 | ... |
| [Ar\textsc{v}] 4740 | 0.034 | ... | ... | ... | ... | ... | 0.56 ± 0.20 | ... |
| H\beta 4861 | 0.000 | 100.0 ± 3.8 | 100.0 ± 5.5 | 100 ± 10 | 100 ± 11 | 100 ± 12 | 100.0 ± 3.3 | 100 ± 14 |
| [O\textsc{iii}] 4959 | −0.025 | 107.4 ± 5.7 | 50.2 ± 5.3 | 96 ± 14 | 107 ± 13 | 18.2 ± 3.1 | 197.7 ± 9.1 | 21.8 ± 4.1 |
| [O\textsc{iii}] 5007 | −0.037 | 274 ± 13 | 120.2 ± 9.8 | 257 ± 31 | 270 ± 16 | 38.6 ± 4.6 | 596 ± 26 | 58.2 ± 6.5 |
| Broad C\textsc{iv} 5808 | −0.191 | 3.34 ± 0.35 | ... | ... | ... | ... | 1.23 ± 0.37 | ... |
| He\textsc{i} 5876 | −0.203 | 16.8 ± 1.3 | 43.9 ± 4.8 | 28.0 ± 5.2 | 16.1 ± 5.6 | 13.8 | 10.28 ± 0.59 | 12.8 |
| [O\textsc{ii}] 6300 | −0.262 | 4.48 ± 0.41 | 11.0 ± 1.9 | 12.4 ± 3.5 | ... | ... | 1.78 ± 0.15 | ... |
| [S\textsc{ii}] 6312 | −0.264 | ... | ... | ... | ... | ... | 2.13 ± 0.15 | ... |
| [N\textsc{ii}] 6548 | −0.295 | 10.5 ± 1.1 | 43.9 ± 4.8 | 15.5 ± 4.9 | 5.5 | 33.8 ± 3.9 | 2.55 ± 0.32 | 52 ± 11 |
| He\textsc{i} 6633 | −0.297 | 282 ± 14 | 279 ± 19 | 281 ± 31 | 281 ± 25 | 284 ± 23 | 282 ± 13 | 281 ± 29 |
| [N\textsc{ii}] 6583 | −0.300 | 30.6 ± 1.8 | 75.4 ± 6.0 | 44.2 ± 6.5 | 28.1 ± 2.6 | 102 ± 9 | 7.06 ± 0.41 | 103 ± 12 |
| He\textsc{i} 6678 | −0.312 | 3.49 ± 0.46 | 4.2 ± 1.4 | ... | ... | ... | 3.23 ± 0.24 | ... |
| [S\textsc{ii}] 6716 | −0.318 | 29.2 ± 1.7 | 62.0 ± 5.1 | 59.2 ± 8.4 | 35.9 ± 3.9 | 60.2 ± 8.5 | 9.90 ± 0.53 | 69 ± 11 |
| [S\textsc{ii}] 6731 | −0.319 | 21.0 ± 1.3 | 46.0 ± 4.0 | 38.3 ± 7.1 | 22.0 ± 3.0 | 37.9 ± 7.8 | 7.33 ± 0.42 | 53 ± 10 |
| He\textsc{i} 7065 | −0.364 | 2.44 ± 0.60 | ... | 1.7 | ... | ... | 2.32 ± 0.31 | ... |
| [Ar\textsc{iii}] 7135 | −0.373 | 7.44 ± 0.58 | 7.4 ± 1.5 | 14.6 ± 3.1 | 10.8 ± 2.4 | ... | 7.20 ± 0.41 | 5.8 |

\( F_{H\beta} \) [10^{14} erg cm^{-2} s^{-1}] 
- \( -W(\text{He}\alpha) \) [Å] 
- \( -W(\text{H}\beta) \) [Å] 
- \( -W(\text{H}\gamma) \) [Å] 
- \( -W(\text{H}\delta) \) [Å] 
Aperture size [arcsec] 
- \( c(H\beta)_{\text{internal}} \) 
- \( E(B-V)_{\text{internal}} \) 
- \( W_{abs} \) [Å] 

4.1 Physical conditions of the ionized gas

We first analyse the nature of the ionization using the so-called diagnostic diagrams, as first proposed by Baldwin, Phillips & Terlevich (1981) and Veilleux & Osterbrock (1987). These diagnostic diagrams plot two different excitation line ratios to classify the excitation mechanism of ionized nebulae. H\textsc{ii} regions (or H\textsc{ii} or starburst galaxies) lie within a narrow band within these diagrams, but when the gas is ionized by shocks, accretion discs or cooling flows (in the case of active galactic nuclei and LINERs), its position in the diagram is away from the locus of H\textsc{ii} regions.

Fig. 11 plots the typical [O\textsc{iii}] \( \lambda 5007/H\beta \) versus [N\textsc{ii}] \( \lambda 6583/H\alpha \) and [O\textsc{iii}] \( \lambda 5007/H\beta \) versus ([S\textsc{ii}] \( \lambda 6716+\lambda 6731 \) )/H\beta diagrams. We used the analytic relations given by Dopita et al. (2000) and Kewley et al. (2001) between different line ratios to check the nature of the excitation mechanism of the ionized gas within the bursts. Actually, the dividing line given by the Kewley et al. (2001) models represents an upper envelope of positions of star-forming galaxies. The left panel of Fig. 11 includes the empirical relation between the [O\textsc{iii}] \( \lambda 5007/H\beta \) and the [N\textsc{ii}] \( \lambda 6583/H\alpha \) provided by Kaufmann et al. (2003), analysing a large data sample of star-forming galaxies from the SDSS (York et al. 2000). As can be seen, all analysed regions lie below the Kewley et al. (2001) theoretical line. This clearly indicates that photoionization is the main excitation mechanism of the gas and that there is very little evidence for a significant contribution from shock excitation. However, this is not satisfied in the case of the centre of NGC 6764 (red cross in Fig. 11), which lies in the region occupied by LINERs. Indeed, this starburst galaxy has been classified as a classical LINER galaxy in the past (Alonso-Herrero et al. 2000).
The electron density of the ionized gas, \(n_e\), was computed via the [S\(\text{II}\)] \(\lambda\lambda6716, 6731\) doublet by making use of the five-level program for the analysis of emission-line nebulae included in the \texttt{IRAF nebular} task (Shaw & Dufour 1995). All regions were found in the low-density limit, \(n_e < 100\) cm\(^{-3}\), and hence we adopt \(n_e = 100\) cm\(^{-3}\).

The electron temperature of the ionized gas was computed for only two galaxies, NGC 1140 and 4861, as only in these two cases is the faint auroral [O\(\text{III}\)] \(\lambda\lambda4959, 5007\) line detectable. We therefore inferred \(T_e([\text{O III}])\) from the [O\(\text{III}\)] \(\lambda\lambda4959, 5007\)/\(\lambda\lambda4363\) ratio by making use of the \texttt{IRAF nebular} task. As we assumed a two-zone approximation to define the temperature structure of the nebula, we used \(T_e([\text{O III}])\) as representative of high-ionization-potential ions. The electron temperature assumed for the low-ionization-potential ions was derived from the linear relationship between \(T_e([\text{O III}])\) and \(T_e([\text{O II}])\) provided by Garnett (1992). The results are listed in Table 6.

### 4.2 Estimation of the chemical abundances

The preferred method for determining oxygen abundances in galaxies using H\(\text{II}\) regions is through electron temperature-sensitive lines such as the [O\(\text{III}\)] \(\lambda\lambda4363\) line, the so-called \(T_e\) method (Peimbert & Costero 1969; Stasinska 1978; Esteban et al. 2004). However, in the absence of the [O\(\text{III}\)] \(\lambda\lambda4363\) line, alternative empirical relationships, such as the \(R_{23}\) method (McGaugh 1991, hereafter M91), \(R_{23} - P\) method (Pilyugin 2001a,b; Pilyugin & Thuan 2005; Pilyugin, Vílchez & Thuan 2010) and \(N_{2}O_2\) method (Kewley & Dopita 2002, hereafter KDO2), which use the strong emission lines, can be used for determining oxygen abundance. However, the use of these empirical methods must be done carefully; see recent reviews by López-Sánchez & Esteban (2010b) and López-Sánchez et al. (2012).

In our case, we can only derive the oxygen abundances of the ionized gas following the \(T_e\) method for two galaxies: NGC 1140 and 4861. We followed the same prescriptions and ionization correction factors (icf) as indicated by López-Sánchez & Esteban (2009) to compute the O, N, S, Ar and Ne abundances, and the N/O, O/S, Ar/O and Ne/O ratios, for the ionized gas within these two galaxies. In particular, we assumed a two-zone scheme for deriving the ionic abundances and considered the Garnett (1992) relation between \(T_e([\text{O III}])\) and \(T_e([\text{O II}])\). We then used the \texttt{IRAF nebular} task (Shaw & Dufour 1995) to compute the ionic abundances from the density of collisionally excited lines. Finally, we assumed the standard icf of Peimbert & Costero (1969) to derive the total N and Ne abundances. For NGC 4861 we have estimates of both the \(S^+/H^+\) and \(S^{++}/H^+\) ratios, and hence we used the icf given by the photoionization models by Stasińska (1978) to derive the total S. The total Ar abundance was calculated by considering the icf proposed by Izotov, Thuan & Lipovetski (1994). The results are compiled in Table 6. Note that we used an updated atomic data set for O\(^+\), S\(^+\) and S\(^{++}\) for nebular. The references for these updated values are indicated in table 4 of García-Rojas et al. (2005).

We derive oxygen abundances, in units of \(12 + \log(O/H)\), of \(8.38 \pm 0.10\) and \(7.95 \pm 0.05\) for NGC 1140 and 4861, respectively. Their associated N/O ratios, in units of \(\log(N/O)\), are \(-1.24 \pm 0.07\) and \(-1.25 \pm 0.08\), respectively. The N/O ratio computed in NGC 1140 agrees with that expected for its O/H ratio (e.g. Izotov & Thuan 1999; Izotov et al. 2004; López-Sánchez & Esteban 2010b). However, the N/O ratio derived for NGC 4861 is clearly higher than that expected for its oxygen abundance. Following the data compiled by these authors, an object with \(12 + \log(O/H)\) between 7.9 and 8.0 should have an N/O ratio between \(-1.6\) and \(-1.4\). Hence, we estimate this excess in the N/O ratio in NGC 4861 to be \(\sim 0.25 - 0.35\) dex. The fact that WR stars are clearly detected in this galaxy suggests that the excess of nitrogen has been released by the ejecta of these massive stars (Kobulnicky et al. 1997; Pustilnik et al. 2004; Brinchmann et al. 2008; López-Sánchez & Esteban 2010b). However, only a few observations confirming the localized N enrichment are available (Kobulnicky et al. 1997; López-Sánchez et al. 2007; James et al. 2009; Monreal-İbro et al. 2010; López-Sánchez et al. 2011), and in some cases the chemical pollution produced by the WR stars detected is not able to explain the observed N excess (Pérez-Montero et al. 2011; Amorín et al. 2012).

For all galaxies (even for the two for which we have a direct estimation of \(T_e\)) we estimate their oxygen abundances using the most common empirical calibrations. Table 7 compiles all the parameters (and their definitions) used for computing the oxygen abundances following these strong-line methods, while Table 8 lists the results. For more information about this method and the equations, see appendix A in López-Sánchez & Esteban (2010b). The KDO2 method using the \(N_{2}O_2\) parameter can only be used for objects with \(12 + \log(O/H) \gtrsim 8.60\), and hence Table 8 gives its value only for such objects.

The final adopted values for the oxygen abundance in each galaxy are computed by averaging all the results provided by these calibrations, and are compiled in Table 8. As has been noted by several authors (Peimbert et al. 2007; Bresolin et al. 2009; López-Sánchez & Esteban 2010b; Moustakas et al. 2010; Rosales-Ortega et al. 2011; López-Sánchez et al. 2012), those empirical calibrations that assume strong emission lines based on photoionization models (McGaugh 1991; Kewley & Dopita 2002) tend to overpredict the observed oxygen abundances derived using the \(T_e\) method and the empirical calibrations based on it (Pilyugin 2001a,b; Pilyugin & Thuan 2005; Pettini & Pagel 2004; Pilyugin et al. 2010) by 0.2–0.4 dex.
Figure 9. Optical spectra of the analysed Wolf-rayet galaxies: (a) NGC 1140, (b) IRAS 07164+5301, (c) NGC 3738, (d) UM 311, (e) NGC 4861 and (f) NGC 3003.
Properties of SF regions within WR galaxies

5 DISCUSSION

5.1 Age of the most recent star-forming event

The estimated age of the most-recent star-forming event can be derived from the Hα equivalent width, $W(\text{H}\alpha)$, of the star-forming knots, because this value decreases with time (e.g. Leitherer & Heckman 1995; Johnson & Conti 2000). We used the predictions

Table 6. Physical conditions and chemical abundances of the ionized gas of the regions analysed in NGC 1140 and 4861.

|          | NGC 1140  | NGC 4861 |
|----------|-----------|-----------|
| $T_e$ [K] | $9500 \pm 900$ | $14000 \pm 600$ |
| $n_e$ [cm$^{-3}$] | $<100$ | $<100$ |
| $12+\log(O^+ / H^+)$ | $8.06 \pm 0.12$ | $7.14 \pm 0.08$ |
| $12+\log(O^{++} / H^+)$ | $8.09 \pm 0.09$ | $7.87 \pm 0.04$ |
| $12+\log(O / H)$ | $8.38 \pm 0.10$ | $7.95 \pm 0.05$ |
| $\log(O^{++} / O^+)$ | $0.03 \pm 0.14$ | $0.73 \pm 0.09$ |
| $12+\log(N^+ / H^+)$ | $6.82 \pm 0.06$ | $5.90 \pm 0.05$ |
| $12+\log(N / H)$ | $7.13 \pm 0.10$ | $6.70 \pm 0.09$ |
| icf(N) | $2.08 \pm 0.21$ | $6.38 \pm 0.95$ |
| $\log(N/O)$ | $-1.24 \pm 0.07$ | $-1.25 \pm 0.08$ |
| $12+\log(S^+ / H^+)$ | $6.10 \pm 0.06$ | $5.36 \pm 0.04$ |
| $12+\log(S^{++} / H^+)$ | ... | $6.16 \pm 0.09$ |
| icf(S) | ... | $1.8 \pm 0.7$ |
| $12+\log(S / H)$ | ... | $6.35 \pm 0.08$ |
| log(S/O) | ... | $-1.59 \pm 0.12$ |
| $12+\log(\text{Ne}^{++} / H^+)$ | $7.48 \pm 0.15$ | $7.01 \pm 0.06$ |
| icf(Ne) | $1.93 \pm 0.65$ | $1.19 \pm 0.22$ |
| $12+\log(\text{Ne} / H)$ | $7.16 \pm 0.19$ | $7.09 \pm 0.10$ |
| log(Ne/O) | $-0.61 \pm 0.16$ | $-0.86 \pm 0.06$ |
| $12+\log(\text{Ar}^{++} / H^+)$ | $5.89 \pm 0.10$ | $5.52 \pm 0.06$ |
| $12+\log(\text{Ar}^{++} / H^+)$ | ... | $4.78 \pm 0.11$ |
| icf(Ar) | $0.69 \pm 0.23$ | $0.46 \pm 0.02$ |
| $12+\log(Ar / H)$ | $5.73 \pm 0.18$ | $5.60 \pm 0.06$ |
| log(Ar/O) | $-2.65 \pm 0.21$ | $-2.35 \pm 0.11$ |
Table 7. Parameters used to derive the oxygen abundance following the strong emission-line methods.

| Galaxy name / Knot | $N_2$ | $N_2O_2$ | $O_3N_2$ | $R_{23}$ | $P$ | $y$ |
|-------------------|-------|----------|----------|---------|-----|-----|
| NGC 1140 / 1      | 0.971 | 0.897    | 1.409    | 6.23    | 0.613 | 0.200 |
| IRAS 07164+5301   | 0.580 | 0.796    | 0.659    | 4.08    | 0.418 | 0.144 |
| NGC 3738          | 0.810 | 1.19     | 1.220    | 10.33   | 0.342 | 0.285 |
| UM 311            | 1.002 | 0.962    | 1.433    | 6.34    | 0.593 | 0.164 |
| NGC 6764 / 1      | 0.446 | 0.141    | 0.0332   | 1.985   | 0.286 | 0.397 |
| NGC 4861 / 1      | 1.602 | 1.10     | 2.37     | 8.82    | 0.900 | 0.953 |
| NGC 3003 / 13     | 0.444 | 0.308    | 0.209    | 2.89    | 0.277 | 0.417 |

The definition of the parameters are:

$N_2 = \log([N\text{II}]/H\alpha)$,

$O_3N_2 = \log([O\text{III}]/H\beta)/\log([N\text{II}]/H\alpha)$,

$N_2O_2 = \log([N\text{II}]/H\alpha)$,

$R_{23} = \log([O\text{III}]/H\beta)+[O\text{II}]/H\beta)$,

$P = (O\text{III}/H\beta)+[O\text{II}]/H\beta)$,

$y = \log([O\text{II}]/H\beta) + [O\text{II}]/H\beta)$.

provided by the Starburst99 code (Leitherer et al. 1999), which are asymptotic giant branch (AGB) phase-corrected. We considered an instantaneous burst with a Salpeter initial mass function (IMF) of 2.35. The lower and upper mass range was taken as 1 to 100 $M_\odot$. We assumed a total mass of 10$^8$ $M_\odot$, and a metallicity of Z/Z_\odot = 0.2, 0.4 or 1, chosen depending on the oxygen abundance of the galaxy derived from our spectroscopic data. The advantage of using W(H\alpha) to derive the age of the most recent starburst event is that it gives a very small error, between 0.1 and 0.5 Myr. Table 4 gives our results. Following our W(H\alpha) data, the majority of the analysed regions experienced a strong star-formation event between 3 and 6 Myr ago. In particular, the starbursts observed in regions 1 of NGC 1140 and 4861 have an age of 5.0 and 4.6 Myr, respectively, in agreement with the fact that we observe WR stars in them.

5.2 Age of the underlying stellar populations

We used the same Starburst99 models to estimate the age of the stellar populations underlying each H II region. We compared Starburst99 model tracks for various colours and metallicities with the colours we derived in each star-forming region and determined the age that best fits the observational data with the predictions given by the models. Although the ages derived using this method have larger uncertainties (typically between 1 and 3 Myr for young stellar populations, and between 100 and 300 Myr for old stellar populations) than the ages determined from the H\alpha equivalent widths, this exercise is useful for discriminating between young ($\leq$25 Myr), intermediate (100–300 Myr) and old (>500 Myr) stellar populations (e.g. Johnson et al. 1999; Méndez & Esteban 2000; Buckalew et al. 2005; López-Sánchez, Esteban & García-Rojas 2006). However, the analysis has to be done with care, as the integrated optical colours of a star-forming region also depend on other factors.

(i) Older stellar populations. We should expect some disagreement between the models and the observational data, as the star-forming regions will actually host mixed stellar populations, with stars that were created in the last starburst event over plotting the points of an older stellar population. In the case of a bright or very recent star-formation event in a region that already has an old underlying population we will obtain high W(H\alpha) values and low $U - B$ colours, but higher $B - V$ or $V - R$ colours than those expected using the models. That is because absorptions in the H\alpha line are expected not to be important in this case (the H\alpha emission line is much stronger than the H\alpha absorption line), and the old, reddish stellar population only weakly affects the emission in the $I$ filter but it strongly affects the $B, V, R$ and $I$ data, being especially important in the infrared filters. Indeed, near-infrared (NIR) data are usually needed to disentangle the effect of the mixed (young/old) stellar populations in strong star-forming galaxies (e.g. Vanzi et al. 2000; Vanzi, Hunt & Thuan 2002; Noeske et al. 2003, 2005; López-Sánchez, Esteban & Rodríguez 2004a,b; López-Sánchez & Esteban 2008).

(ii) Emission from the ionized gas. Theoretical models, as those used here, consider only the emission of the stellar continuum to obtain the broad-band colours, but the contribution of the emission lines coming from the ionized gas may be important in some cases. The value of these corrections depends on several factors (position of the emission lines within the broad-band filters, metallicity and ionization of the gas, ratio between the region occupied by the H II region and the area covered by the slit), and it is not easy to provide an average number. Nevertheless, we used the values

Table 8. Oxygen abundances derived for our Wolf–Rayet galaxy sample using the most commonly used strong emission-line methods. The last two columns give the adopted oxygen abundance and the branch (lower, medium or upper). The third column lists previous estimations of the O/H ratio in the literature. The strong emission-line calibrations are: M91, McGaugh (1991); KD02, Kewley & Dopita (2002); PT05, Pilyugin & Thuan (2005); P01, Pilyugin (2001a,b); PP04a, Pettini & Pagel (2004), using a linear fit to the $N_2$ parameter; PP04c, Pettini & Pagel (2004), using the $O_3N_2$ parameter.

| Galaxy name / Knot | T_e | Lit. | M91 (R_{23}, P) | KD02 (R_{23}, P) | KOD2 (N_2O_2) | PT05 (P) | P01 (P) | PP04a (N_2) | PP04c (N_2O_3) | Adopted$^a$ (MKD) |
|-------------------|-----|------|----------------|-----------------|----------------|----------|---------|-------------|----------------|------------------|
| NGC 1140 / 1      | 8.38 | 0.10 | 0.829 ± 0.09$^b$ | 8.61            | 8.36            | 8.26     | 8.35    | 8.30        | 8.56            | 8.36             |
| IRAS 07164+5301   | ...  | 8.96 | 0.77           | 8.77            | 8.42            | 8.50     | 8.57    | 8.52        | 8.89            | 8.50             |
| NGC 3738          |     |     | 8.97           | 8.99            | 8.18            | 8.26     | 8.44    | 8.35        | 8.55            | 8.31             |
| UM 311            | 8.31 | 0.04 | 8.31           | 8.53            | 8.12            | 8.15     | 8.33    | 8.28        | 8.37            | 8.22             |
| NGC 6764 / 1      |     |     | 9.07           | 8.90            | 8.53            | 8.68     | 8.65    | 8.72        | 9.05            | 8.65             |
| NGC 4861 / 1      | 7.95 | 0.05 | 8.05 ± 0.04$^c$ | 8.03            | 7.77            | 7.83     | 7.99    | 7.97        | 8.13            | 7.89             |
| NGC 3003 / 13     |     |     | 9.00           | 8.87            | 8.41            | 8.56     | 8.65    | 8.66        | 8.98            | 8.57             |

$^a$Average abundance value using all the empirical methods; the T_e method is not considered here. We provide two results: PPP, which considers the average value obtained with the PT05, P01, PP04a and PP04c calibrations; and MKD, which assumes the average value of the M91 and KD02 calibrations. The KD02 method using the N_2O_2 parameter is considered only for objects with 12-log(O/H) $\geq$ 8.60 dex (NGC 3738, 6764 and 3003). The uncertainty in these values is ±0.10 dex.

$^b$Moll et al. (2007) through the T_e method.

$^c$Taken from the literature (Huang et al. 1996) through the T_e method, although we consider that this value is not correct; see Section 5.4.2.

$^d$Martin (1997).

$^e$Izotov & Thuan (1998).

$^f$Esteban et al. (2009).
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Figure 12. $U - B$ versus $B - V$ diagrams comparing the predictions given by evolutionary synthesis models provided by the Starburst99 code (Leitherer et al. 1999) with the colours obtained from the star-forming regions within the Wolf–Rayet galaxies of our sample. The metallicity of each model is also shown, and it is $Z = 0.008$ in panel (a) NGC 1140, IRAS 07164+5301, NGC 3738 and UM 311; $Z = 0.02$ in panel (b) NGC 6764; $Z = 0.04$ in panel (c) NGC 4861; and $Z = 0.02$ in panel (d) NGC 3003. The vector $E(B - V) = 0.323$ mag [$A_V = 1$, $(U - B) = -0.232$, $(B - V) = -0.337$] used for dereddening the data is also shown.

For $\sim 40$ independent regions analysed by López-Sánchez & Esteban (2008) – see their appendix A – and tabulated in their table 6 to ascertain some estimates of the correction of the broad-band colours for the emission of the gas according to the $W(H\alpha)$ value. For $W(H\alpha) \sim -50$ Å we find $\Delta(U - B) = -0.01$, $\Delta(B - V) = 0.03$ and $\Delta(V - R) = -0.02$ mag, and hence for these cases the contribution should be within the errors. For $W(H\alpha) \sim -200$ Å, we have $\Delta(U - B) = -0.05$, $\Delta(B - V) = 0.10$ and $\Delta(V - R) = -0.10$ mag. For these cases we should take into account the contribution of the emission lines; doing so increases the uncertainties of the ages derived using the broad-band filters for these knots. Finally, in the case of $W(H\alpha) \sim -1000$ Å, we have $\Delta(U - B) = -0.1$, $\Delta(B - V) = 0.6$ and $\Delta(V - R) = -0.2$ mag. We have a few knots with $W(H\alpha) \lesssim -1000$ Å (see Table 4).

(iii) Extinction. This will move the broad-band colours to redder values. The intrinsic extinction can be determined from the $c(H\beta)$ derived from spectroscopy; however, here we use a different approach to estimate the internal extinction on each knot using the $U - B$ versus $B - V$ diagram.

Fig. 12 plots the Starburst99 model tracks for the $U - B$ versus $B - V$ colour–colour diagram; the colours derived for our star-forming knots are overlaid onto these model tracks. As previously specified, we have corrected our broad-band colours for Galactic extinction using only the Schlegel et al. (1998) data. Assuming that the offset between our data points and the models is caused by the reddening, we can estimate the intrinsic extinction, $E(B - V)_{\text{internal}}$, of each knot. For this, we use the reddening vector in the $U - B$ versus $B - V$ diagram, $(U - B) = -0.232$, $(B - V) = -0.337$, to move our data points to the colour–colour model track. The magnitude of movement provides $E(B - V)_{\text{internal}}$, which we list in Table 9. Note that this cannot be done for all knots, as sometimes the
### Table 9. Estimates of the internal reddening, $E(B - V)_\text{internal}$, and the ages of the young and old stellar populations of the analysed knots using the broad-band colours. The second-last column compiles our best estimates for the age of the most recent star-formation event, and considers the data derived using both the Hα images and the spectroscopy. The uncertainty for the ages of the young stellar populations typically is $\sim$1 Myr. The uncertainties of the age of the underlying stellar population vary from $\sim$10–20 Myr (ages up to 100 Myr) to $\sim$100–300 Myr (ages up to 100 Myr). The typical uncertainty for $E(B - V)_\text{internal}$ is 0.05 mag.

| Galaxy      | $Z$ [d] | Knot | $E(B - V)_\text{internal}$ [mag] | Ages estimated from broad-band colours | Age adopted | Burst [Myr] | Underlying [Myr] |
|-------------|---------|------|----------------------------------|----------------------------------------|-------------|------------|-----------------|
| NGC 1140    | 0.008   | 1    | 0.1                              | 5.2–5.4                                | 5.0 20      | 100        | 20              |
|             |         | 2    | 0.2                              | 5.2–6.2                                | 5.5 25      | 100        | 20              |
|             |         | 3    | 0.0\(d\)                         | 3.3–3.8                                | 3.5 50      | 100        | 20              |
|             |         | 4    | 0.0\(d\)                         | 3.2–3.3                                | 3.2         | 100        | 20              |
| IRAS 07164+5301 | 0.008 | 1    | 0.0                              | 5.9–6.3                                | 6.0 25      | 100        | 25              |
| NGC 3738    | 0.008   | 1\(a\) | 0.00–0.25                       | 5.0–7.0                                | 6.0 600     | 100        | 600             |
| UM 311      | 0.008   | 1\(b\) | 0.00–0.17                        | 3.2–3.7                                | 3.2         | 100        | 30              |
| NGC 6764    | 0.02    | 1    | 0.0                              | 3.5–9.0                                | 6.0 400     | 100        | 400             |
|             |         | 2\(c\) | 0.0                             | 4.0–10                                 | 6.0 15      | 100        | 15              |
|             |         | 3    | 0.0                              | 3.4–6.0                                | 5.0 400     | 100        | 400             |
| NGC 4861    | 0.004   | 1\(b\) | 0.0–0.5                         | 3.5–5.0                                | 4.6         | 100        | 40              |
|             |         | 2\(b\) |                                 | 3.1–4.8                                | 3.0         | 100        | 30              |
|             |         | 3\(b\) |                                 | 4.8–6.4                                | 5.0 25      | 100        | 25              |
|             |         | 4    | 0.0                              | 4.1–4.8                                | 4.5         | 100        | 25              |
|             |         | 5    | 0.0                              | 4.1–5.0                                | 5.0 30      | 100        | 30              |
|             |         | 6    |                                 | 5.2–6.8                                | 5.6 50      | 100        | 50              |
|             |         | 7    | 0.1                              | 2.6–4.1                                | 4.0 15      | 100        | 15              |
|             |         | 8    | 0.0                              | 3.1–4.6                                | 4.5 30      | 100        | 30              |
|             |         | 9    | 0.0                              | 7.2–10                                 | 5.0 20      | 100        | 20              |
|             |         | 10   |                                 | 3.1–5.4                                | 4.5         | 100        | 30              |
|             |         | 11   | 0.0                              | 4.8–6.6                                | 5.0         | 100        | 30              |
|             |         | 12\(a\) | 0.00–0.25                      | 2.5–4.0                                | 3.7 100     | 100        | 100             |
| NGC 3003    | 0.02    | 1    |                                 | 2.0–3.0                                | 3.0         | 100        | 100             |
|             |         | 2    | 0.2                              | 3.0–5.0                                | 5.0 500     | 100        | 500             |
|             |         | 3    | 0.4                              | 4.5–10                                 | 8.0 20      | 100        | 20              |
|             |         | 4    | 0.0                              | 3.4–6.1                                | 5.5         | 100        | 50              |
|             |         | 5\(b\) |                                 | 3.3                                    | 3.3         | 100        | 30              |
|             |         | 6    | 0.0                              | 5.8–6.5                                | 5.5 20      | 100        | 20              |
|             |         | 7    | 0.0                              | 60–120                                 | 5.6 600     | 100        | 600             |
|             |         | 8    | 0.0                              | 3.2–3.4                                | 3.4         | 100        | 200             |
|             |         | 9    | 0.5                              | 4.5–10                                 | 4.5         | 100        | 500             |
|             |         | 10\(b\) |                                 | 3.2–3.4                                | 3.1         | 100        | 30              |
|             |         | 11   |                                 | 1.9–6.1                                | 4.7         | 100        | 40              |
|             |         | 12   | 0.3                              | 3.0–5.5                                | 5.3         | 100        | 300             |
|             |         | 13\(0.0–0.6d\) | 100–175 >1000 >1000 >1000 >1000 | 6.7         | 100        | 1000         | 1000            |
|             |         | 14   |                                 | 6.3–6.6                                | 6.2         | 100        | 500             |
|             |         | 15   | 0.4                              | 5.5–9.5                                | 6.0         | 100        | 500             |
|             |         | 16   | 0.3                              | 3.4–3.5                                | 3.5         | 100        | 100             |
|             |         | 17   | 0.0                              | 15–50                                  | 4.0         | 100        | 200             |
|             |         | 18   | 0.2                              | 5.8–9.6                                | 6.2         | 100        | 200             |
|             |         | 19   |                                 | 6.1–6.4                                | 5.8         | 100        | 100             |
|             |         | 20   | 0.2                              | 5.6–6.0                                | 5.8         | 100        | 20              |
|             |         | 21   | 0.0                              | 55–150                                 | 6.0         | 100        | 100             |
|             |         | 22   | 0.4                              | 5.5–6.2                                | 5.6         | 100        | 40              |
|             |         | 23\(b\) | 0.0–0.1                           | 2.4–3.6                                | 3.4         | 30         | 30              |
|             |         | 24   | 0.2                              | 2.2–3.2                                | 3.4         | 100        | 500             |
|             |         | 25   |                                 | 3.3–3.4                                | 3.4         | 100        | 800             |

\(a\) The derived $E(B - V)_\text{internal}$ for this object is very probably overestimated because of the effect of an important old stellar population underlying the burst on the $B - V$ colour. See text for details.

\(b\) The broad-band colours of these knots, especially $B - V$, are probably strongly affected by the emission of the ionized gas. See text for details.

\(c\) The centre of NGC 6764 (knot 2) is a LINER, and not a star-forming region. Hence, these values are meaningless. See text for details.

\(d\) As these knots have a relatively large $W$(Hα), it is possible that the contribution of the emission of the gas cannot be neglected. If this is true, the real value of the intrinsic reddening may be up to $E(B - V)_\text{internal} \sim 0.4$ mag. See text for details.
movement of our data points following the reddening vector puts them away from the theoretical track (e.g. knots 5, 10, 11, 14, 19 and 25 in NGC 3003). This is typically the case for faint regions where the uncertainties are large, but it may also be a consequence of the emission of the gas. As detailed above, the effect of the emission lines in the $B - V$ colour may be important, even $+0.6\,\text{mag}$. This is what may be happening in UM 311, in knots 1, 2, 3 and 12 of NGC 4861, and in knots 5, 10 and 23 of NGC 3003, which show the lowest $W$(H$\alpha$) values of our sample. In particular, it seems to be the case for knot 1 of NGC 4861, the strongest star-forming region in our sample (see Fig. 8). The $E(B-V)_{\text{internal}}$ value we computed for this knot using our spectrum is $\sim0.03\,\text{mag}$, but we need an offset of $\sim0.5\,\text{mag}$ to account for its position in Fig. 12(c). On the other hand, there are two regions with relatively low $W$(H$\alpha$) values, namely knots 3 and 4 of NGC 1140 which have $W$(H$\alpha$) $\sim -900\,\text{Å}$, that show a good agreement with the models without the need to correct the observed colours for the emission of the gas. Perhaps in these two very young star-forming regions there is a contribution from both internal reddening (which moves the $B - V$ colour to redder values) and the emission of the gas (which moves the $B - V$ colour to bluer values), meaning that the net contribution of the two effects is null. As the maximum variation of the $B - V$ colour because of the emission of the gas is $\Delta(b - v) \sim 0.4$, we should expect that the highest value of the internal reddening in these two regions is $E(B-V)_{\text{internal}} \sim 0.4\,\text{mag}$. However, spectroscopic data are needed to confirm this hypothesis.

Furthermore, we consider that the offset between the position of knot 13 of NGC 3003 (the centre of the galaxy) and the theoretical model is mainly because of the presence of a very important old stellar population underlying this star-forming region. Indeed, this knot has a high $W$(H$\alpha$) value, $-90\,\text{Å}$, and hence we expect that the emission of the gas is negligible. On the other hand, the $E(B-V)_{\text{internal}}$ value derived using our spectrum, $\sim0.03\,\text{mag}$, is too low in comparison with the offset of $\sim0.6\,\text{mag}$ needed to match with the model following the reddening vector (an arrow mark as shown in Fig. 7). Finally, the circular aperture used for this knot (see Fig. 7) leads to the inclusion not only of the starburst but also of a large non-star-forming region probably dominated by older stellar populations.

In the case of NGC 3738 we derive $E(B-V)_{\text{internal}} = 0.25\,\text{mag}$ following the $U - B$ versus $B - V$ colour–colour diagram. However, for this galaxy we adopted $E(B-V)_{\text{internal}} = 0\,\text{mag}$ using our spectroscopic data. The starburst is located in the centre of this galaxy, which hosts an extended disc-like structure (see Fig. 3) composed of older stars. Hence, we suspect that there is also an important contribution from this old stellar population to the optical broad-band colours of the star-forming region.

The values for the intrinsic extinction calculated using our photometric data of knot 1 of NGC 1140, IRAS 07164+5301, and knot 1 of NGC 6764 ($0.0 \pm 0.3\,\text{mag}$ in all cases) match well the values derived from our optical spectroscopy data (adopted 0 mag for the first object, and derived 0.041 $\pm 0.014\,\text{mag}$ and 0.014 $\pm 0.007\,\text{mag}$ for the second and third knots). This also suggests that the correction for the emission of the gas is not critical in these objects.

Once the intrinsic reddening is determined, we estimate the age of the young stellar population from the reddening-corrected $U - B$ colour and compare it with that derived from the $W$(H$\alpha$). The second-last column in Table 9 gives the age adopted for each burst, with a typical uncertainty of 1 Myr.

We further check the agreement between the data and ages derived using the narrow-band H$\alpha$ images and the broad-band optical colours. Fig. 13 compares the $W$(H$\alpha$) obtained using our H$\alpha$ image with the $U - B$ colour derived for each knot. We also plot the predictions given by evolutionary synthesis models provided by the Starburst99 code for several metallicities, as well as the $W$(H$\alpha$) obtained using our spectroscopic data (yellow points). We find a relatively good agreement between all measurements. However, in the cases of NGC 4861 (knots 3 and 9) and NGC 3003 (knots 7, 13, 17 and 21) we find regions that are located far from the models. The reason for this discrepancy is the effect of an important intermediate–old stellar population underlying the bursts.

Finally, we use again the predictions given by the Starburst99 models and the values obtained for the rest of the colours to obtain an estimate of the age of the dominant stellar population underlying the starburst of each knot. For this we especially consider the results coming from the $V - R$ and the $V - I$ colours. The ages adopted for the underlying stellar populations are given in the last column of Table 9. As can be seen, knots in NGC 3738, 6764 and 3003 usually have old underlying stellar populations, with ages even older than 500 Myr in many cases. However, the rest of the galaxies (NGC 1140, IRAS 07164+5301, UM 311 and NGC 4861) host relatively young underlying stellar populations (20–50 Myr), which suggests that the strong star-formation activity observed in these galaxies has been ongoing for that period.

### 5.3 Analysis of the WR features

A magnified view of the spectrum of NGC 1140 around 4650 Å is presented in the top-left panel of Fig. 14. The blue WR bump at around 4686 Å, which was previously reported by Guseva et al. (2000), is identified in this spectrum, although with a low S/N. However, the red WR bump around C$\lambda\lambda5808$ can be clearly identified in this object, as seen in the top-right panel of Fig. 14. We detect both WR features in the spectrum of the low-metallicity galaxy NGC 4861. In this case, both the broad and the narrow He$\pi\lambda4686$ emission lines are observed (see bottom row in Fig. 14).

In order to quantify the fluxes of the WR features detected in these two galaxies, we fitted a broad and a narrow Gaussian for the stellar and nebular WR lines for each WR bump. In the case of the red WR bump we considered only a broad C$\lambda\lambda5808$ component, as no narrow emission is observed. These fits are included in Fig. 14, which also shows the residual spectrum after subtracting our fitted model to the observed spectrum. The derived fluxes for the blue and red WR bumps in each case—considering only the broad component—have been compiled in Table 5.

We followed the procedure described in Guseva et al. (2000) to derive the number of WR stars and the WR/(WR+O) and WCE/WNE ratios in NGC 1140. Using the values for the flux of the broad He$\pi\lambda4686$ and C$\lambda\lambda5808$ emission lines derived from our fits (see Table 5) and considering the metallicity dependence of the WR luminosities—equations (7) and (8) in López-Sánchez & Esteban (2010a), which considered both the broad-line WNL and WCE luminosities given by Crowther & Hadfield (2006) for solar and $Z_C/50$ metallicities—we derive WNL $\sim 92 \pm 36$ and WCE $\sim 59 \pm 15$. From the total luminosity of the H$\beta$ line and considering their equation (10), we find that the total number of O stars in the burst is $1553 \pm 300$. However, the contribution of the WR stars and other O star subtypes to the ionizing flux must be considered. This is undertaken via the $N_{O7V}(t) = N_{O7V}/N_{W}$; where $N_{O7V}$ and $N_{W}$ represent number of O7V and O stars, respectively (Vacca & Conti 1992; Vacca 1994; Schaefer & Vacca 1998), which depends on the age of the burst. Considering the age of the most recent star-formation event ($\sim5.0\,\text{Myr}$, see Table 9) and the models provided by Schaefer...
Figure 13. \(W(H\alpha)\) versus \(U - B\) diagrams comparing the predictions given by evolutionary synthesis models provided by the Starburst99 code (Leitherer et al. 1999) with the colours obtained from the star-forming regions within the Wolf-Rayet galaxies of our sample. The metallicity of each model is shown. The yellow points indicate that the \(W(H\alpha)\) value is from our spectroscopic data (see Table 5). Except for the case of IRAS 07164+5301, the yellow data points are connected to the values derived using our \(H\alpha\) images for the same knot.

\& Vacca (1998), we assumed \(\eta_0(t) \sim 0.25\) for this object. We then derive a WR/(WR+O) ratio of 0.089 ± 0.034 and a WCE/WNL ratio of 0.64 ± 0.30. Both values agree well with the ratios expected for an object with the oxygen abundance of NGC 1140. We note that our estimates of the WR/(WR+O) and WCE/WNL ratios are similar, within the errors, to those derived by Moll et al. (2007) using HST data, WR/(WR+O) = 0.11 and WCE/WNL = 0.36. However, their estimates of the total number of O and WR stars are around four times the values we derive here. The reason for this discrepancy is that we are probably observing a slightly different area within the galaxy and using a different aperture size.

We repeated this procedure for NGC 4861, a low-metallicity galaxy also showing both the broad He\(\text{II}\) \(\lambda4686\) and C\(\text{IV}\) \(\lambda5808\) emission lines. Note that for this object we subtracted the flux of the nebular, narrow He\(\text{II}\) \(\lambda4686\) emission line to obtain an accurate estimate of the flux of the broad He\(\text{II}\) \(\lambda4686\) emission line. In this case, we derive WNL = 225 ± 35, WCE = 67 ± 30 and O = 4336 ± 1200, assuming the appropriate oxygen abundance for the WR luminosities and \(\eta_0(t) \sim 0.25\) considering that the age of the most recent starburst is \(\sim 4.6\) Myr, see Table 9. Hence, we estimate that the WR/(WR+O) and the WCE/WNL ratios for NGC 4861 are 0.062 ± 0.021 and 0.30 ± 0.12, respectively. Both the values are also in agreement with the WR ratios expected for a galaxy with its metallicity.

Although the centre of the galaxy NGC 6764 also shows some broad emission lines around the He\(\text{II}\) \(\lambda4686\) emission feature, which may be attributable to WR stars, the fact that the ionization nature of this object is not photoionization (see Section 4.1) prevents us from deriving any realistic estimate of the number of WR stars in this region.
5.4 Analysis of individual galaxies

5.4.1 NGC 1140

NGC 1140 is a SbPec galaxy located at a distance of 17.9 Mpc. It is an object showing blue colours, $B - V = 0.01 \pm 0.02$ mag, and intermediate metallicity, $12 + \log(O/H) = 8.38 \pm 0.10$. Hunter, O’Connell & Gallagher (1994a) used optical broad-band images, Hz data, optical spectroscopy and neutral hydrogen observations to identify the central giant star-forming region and a chain of other star-forming regions coinciding with the low-light-level extension in the south-west tail of the galaxy (see Fig. 1). Later, Hunter, van Woerden & Gallagher (1994b) used HST data to show that the central region consists of a supergiant H II region and a few super-star clusters with sizes of $< 10$ pc. With our ground-based images it is not possible to resolve the individual clusters observed by the HST in the central giant H II region, and hence it has been considered as a single star-forming region (knot 1). The other star-forming knots, numbered 2, 3 and 4, which are in the south-west part of the galaxy, also show very blue colours. In fact, knots 3 and 4 are bluer than the central knot. The bluer colour of the outer body of the galaxy indicates that extensive star formation is occurring throughout this galaxy.
Indeed, using the optical colours we are not able to detect stars older than 25–50 Myr underlying the starburst. The age of the most recent burst decreases from the centre (~5.0 Myr) to the external regions (~3.2 Myr) of NGC 1140, suggesting that the arc-like plume where they are located originated very recently.

WR features were previously detected in NGC 1140 by Guseva et al. (2000) and Moll et al. (2007). We certainly detect both the blue and red WR bumps (see Fig. 14), this last one being particularly prominent. As discussed above, the derived WR properties within NGC 1140 agree well with those expected for a galaxy with its metallicity (Guseva et al. 2000; López-Sánchez & Esteban 2010a).

The SFRs calculated using the Hα flux for the four knots reveal that the central region (knot 1) is undergoing an intense starburst, while the other three star-forming knots have a moderate rate of star formation.

Our estimate of the SFR within this galaxy is 0.65 M⊙ yr⁻¹, which agrees well with those determined by Hunter et al. (1994b) (0.8 M⊙ yr⁻¹) and Moll et al. (2007) (0.7 ± 0.3 M⊙ yr⁻¹). FIR and 20-cm radio-continuum data are available for this galaxy. Using the flux densities for 60 and 100 μm provided by IRAS (Infrared Astronomical Satellite, Moshir et al. 1990) and applying the relationships provided by Condon (1992) and Kennicutt (1998), we derive SFR_{60μm} = 0.25 M⊙ yr⁻¹ and SFR_{100μm} = 0.30 M⊙ yr⁻¹, respectively. On the other hand, considering the 1.4-GHz flux for this galaxy provided by Hunter et al. (1994a) and the Condon, Cotton & Broderick (2002) calibration, we derive SFR_{1.4GHz} = 0.20 M⊙ yr⁻¹. Hence, the SFR values derived using the FIR and radio data are 2–3 times lower than our Hα-based SFR.

Considering the enhancement of SF activity at its centre and its peculiar optical and H I morphology, Hunter et al. (1994a,b) concluded that NGC 1140 has undergone recent violent disturbances that may be explained by assuming a merger of two low-surface-brightness galaxies. Our new data agree with this scenario. Hence, NGC 1140 seems to be another example of a WR galaxy in which starburst has been triggered by galaxy interactions, as was found for the majority of the objects analysed by López-Sánchez (2010).

5.4.2 IRAS 07164+5301

IRAS 07164+5301 is known as an extreme starburst source (Allen et al. 1991). The optical spectrum of the galaxy was previously studied by Huang et al. (1996), but the broad-band colours of IRAS 07164+5301 are analysed here for the first time. We report blue colours in this galaxy: \( U - B = -0.47 ± 0.05 \), \( B - V = 0.06 ± 0.04 \), \( V - R = 0.06 ± 0.05 \) and \( V - I = 0.30 ± 0.02 \). The comparison of the derived optical colours with the stellar population synthesis models and the analysis of the equivalent width of the Hα emission line provide an age of ~6.5 Myr for the most recent star-formation event. Interestingly, the optical colours do not show the presence of an important old stellar population underlying the starburst. The oldest age we derive for the dominant stellar populations in this galaxy is ~25 Myr.

The youth of the starburst agrees with the detection of WR features in the optical spectrum of the galaxy analysed by Huang et al. (1996), who reported the presence of broad lines around 4686 Å, suggesting the presence of N III λ4640, C III λ4650 and He II λ4686. These authors also indicated a tentative detection of O VI λ5835 and a lack of C IV λ5808. However, we do not detect any of these features, even though our spectrum is of a quality similar to or even better than the spectrum presented by Huang et al. (1996).

We derive an oxygen abundance of 12 + log(O/H) = 8.50 for IRAS 07164+5301. This value is much lower than the metallicity obtained by Huang et al. (1996), who found 12 + log(O/H) = 8.96 using the direct method. However, their estimate of the [O III] λ4363 flux is very probably an overestimate, and even its detection is not clear because of both the relatively low S/N and the spectral resolution (4.7 Å pixel⁻¹) of their spectrum. Taking into account that we have estimated the oxygen abundance of this object using several parameters (N_{2}, N_{2}O_{3}, R_{23}, P) and calibrations, all giving similar values (except for the caveat of those methods based on photoionization models, as discussed above), we consider that our metallicity estimation of IRAS 07164+5301 is more appropriate than that obtained by Huang et al. (1996).

Using our data we compute a radial velocity of \( V_r = 12981 \text{ km s}^{-1} \) (redshift \( z = 0.0433 \)) for IRAS 07164+5301. Hence this galaxy lies at a distance of 177 Mpc. The high radial velocity this galaxy possesses is the reason we cannot detect its Hα emission using the rest-frame Hα filter. However, we used the flux of the Hα line observed in our optical spectrum to estimate a SFR of ~7.6 M⊙ yr⁻¹. Using the FIR and 20-cm radio-continuum data available for this galaxy, we derive SFR_{60μm} = 8.3 M⊙ yr⁻¹, SFR_{FIR} = 8.1 M⊙ yr⁻¹, and SFR_{1.4GHz} = 5.7 M⊙ yr⁻¹. The 1.4-GHz data were provided by Condon et al. (1998). All these values are in excellent agreement with the SFR we have estimated here using the Hα emission.

5.4.3 NGC 3738

NGC 3738 is classified as an irregular (de Vaucouleurs et al. 1991), low-metallicity galaxy. As it has a very low radial velocity, \( V_r = 229 \text{ km s}^{-1} \), it is not easy to estimate the distance to this galaxy, and hence the best estimates of its distance range from 4.0 to 4.5 Mpc (Hunter 1982; Hunter, Gallagher & Rautenkranz 1982; Hunter & Hoffman 1999). The distance value listed in Table 1 for this galaxy, \( d = 5.56 \text{ Mpc} \), comes just from the value of the Hubble constant. However, the most recent distance estimate for this galaxy using the luminosity of the tip of the red giant branch stars is 4.90 Mpc (Karachentsev et al. 2003).

The optical spectrum of NGC 3738 resembles those of H II regions with emission dominated by massive, hot stars. Martin (1997) notes the presence of a broad He II λ4686 emission line in the integrated spectrum of this galaxy, and hence NGC 3738 was also listed as a WR galaxy by Schaerer et al. (1999). However, our optical spectrum does not show any faint WR features.

We used the bright emission lines to estimate the metallicity of the galaxy, namely 12 + log(O/H) = 8.31. This value was obtained by averaging the results provided by both the high- and low-branch metallicity calibrations, and agrees within the uncertainties with the result obtained by Martin (1997), which was 12 + log(O/H) = 8.23.

NGC 3738 has a bright star-forming region at its centre, for which we derive a SFR of 0.035 ± 0.003 M⊙ yr⁻¹. Our result agrees well with the SFR estimation obtained using the Hα flux provided by Kennicutt et al. (2008) for this galaxy, namely 0.030 M⊙ yr⁻¹. Using the FIR fluxes available for this galaxy and the same equations as cited in the previous subsection we derive SFR_{60μm} = 0.015 M⊙ yr⁻¹ and SFR_{FIR} = 0.018 M⊙ yr⁻¹. These values are just slightly lower than the SFR derived using the Hα images.

The age of the most recent star-formation event we estimate for this galaxy using both the \( W(Hα) \) and the \( U - B \) colour is 6.0 Myr. However, from the \( B - V \) and, especially, \( V - R \) and \( V - I \) colours it is clear that the galaxy possesses a very important old stellar population underlying the starburst, for which we estimate an age of ~600 Myr.
UM 311

UM 311 is an intriguing extragalactic H II region that shows a radial velocity of \( V_\text{r} = 1675 \text{ km s}^{-1} \). Therefore the distance to this galaxy is 18.7 Mpc. An essential note in NED defines UM 311 as an ‘H II region in the GPair CGCG 0113.0-0107’. Our optical images (see Fig. 4) clearly show two galaxies in apparent interaction, a spiral galaxy (NGC 405) and a dwarf elliptical to the north-east (UGC 807), which have radial velocities of 1761 and 11 431 km s\(^{-1}\), respectively. Therefore, these two galaxies are not physically associated. Because of the very similar radial velocity, UM 311 may indeed be an H II region within NGC 405. However, its observed properties (blue colours, compactness and intensity of the star-formation activity) do not rule out the possibility that it is an independent blue compact dwarf galaxy (BCDG) that is interacting with the spiral galaxy NGC 405. A similar example of a BCDG interacting with a spiral galaxy is the stunning NGC 1512 / NGC 1510 system (Koribalski & López-Sánchez 2009). Interferometric H I data are needed to completely elucidate this issue.

The first study reporting the presence of WR stars in UM 311 was presented by Masegosa, Moles & del Olmo (1991), who detected the broad He II \( \lambda 4686 \) emission line. Since then many authors have analysed the WR content of this object. Izotov & Thuan (1998) confirmed the presence of both the blue and the red WR bumps. Guseva et al. (2000) noted that the blue WR bump was particularly strong. Pindao (1999), Buckalew et al. (2005), Zhang et al. (2007) and Brinchmann et al. (2008) also included UM 311 in their studies of WR galaxies. However, the poor quality of our optical spectrum does not allow us to detect the faint broad features attributed to WR stars. We find that the age of the most recent starburst is 3.2 Myr; however, using the optical colours we are not able to observe the underlying old stellar population. This fact indicates the strength of the starburst in UM 311.

UM 311 has also been used in the analysis of the chemical abundances of low-metallicity extragalactic H II regions (e.g. Izotov & Thuan 1998, 1999; Izotov et al. 2004; Izotov et al. 2006; Pilyugin 2001a), and hence its oxygen abundance has been determined with good precision, namely \( 12 + \log(O/H) = 8.31 \pm 0.04 \) (Izotov & Thuan 1998). Using several empirical calibrations and the data provided by our optical spectrum, we estimate that the oxygen abundance of UM 311 is \( 12 + \log(O/H) = 8.27 \), in excellent agreement with the previous estimates.

Using our H I images, we derive a SFR of \( 0.065 \pm 0.005 \) M⊙ yr\(^{-1}\). This value is very low compared with the SFR derived by Hopkins, Schulte-Ladbeck & Drozdovsky (2002) using FIR and radio-continuum data, SFR\(_{\text{FIR+radio}} = 1.5 \) M⊙ yr\(^{-1}\) and SFR\(_{\alpha} \leq 1.1 \) M⊙ yr\(^{-1}\). However, we consider that our SFR estimation is more appropriate, as neither the FIR nor the radio-continuum images are of high enough spatial resolution to resolve UM 311 within the spiral galaxy NGC 405.

NGC 6764

NGC 6764 is a barred spiral (SBb type) galaxy (see Fig. 5), which is also classified as a classical LINER galaxy (Alonso-Herrero et al. 2000). Indeed, using optical emission line ratios we can confirm that the nucleus of this galaxy lies in the LINER region of the diagnostic (or Baldwin, Phillips & Terlevich) diagram for emission-line galaxies (Fig. 11). Osterbrock & Cohen (1982) note the presence of broad N III \( \lambda 4640 \) and He II \( \lambda 4686 \) emission lines in the spectrum of the nucleus of NGC 6764. These features were later reported by Eckart et al. (1996), Guseva et al. (2000) and Fernandes et al. (2004). Osterbrock & Cohen (1982) also reported a signal of excessive widths of He I \( \lambda 5876 \) and Hα, which they attributed to emission from WR stars. Indeed, broad C IV \( \lambda 5896 \) and C IV \( \lambda 5808 \) lines from WC stars were discovered by Fernandes et al. (2004). Our optical spectrum confirms the broad features in the blue WR bump, although the existence of the red WR bump is not clear (see Fig. 10). However, as the photoionization is not caused by massive stars, we cannot compute the WR content in this object.

From our Hα images of NGC 6764 we identify three regions showing ionized gas emission: the centre of the galaxy (knot 2) and the regions located at the end of the bar (knot 3 to the east; knot 1 to the west). The starburst activity in NGC 6764 was first observed by Eckart et al. (1991, 1996), who revealed a dense concentration of molecular gas and very recent (few tens of Myr) starburst in the nucleus of NGC 6764. Indeed, we estimate an age of \( \sim 15 \) Myr for the dominant stellar population in the centre of the galaxy, although the \( U - B \) colour and the W(Hα) suggest that the age of the most recent starburst is \( \sim 6 \) Myr. This value agrees with the result obtained by Leon et al. (2007), who concluded that the nuclear starburst is 3–7 Myr old using their analysis of the interaction between the central activity and the molecular gas. However, knots 1 and 3 show an important stellar population underlying the bursts, which has an age of \( \sim 400 \) Myr.

We cannot compute the oxygen abundance of the nucleus of the galaxy because of its LINER nature. However, we derive a metallicity of \( 12 + \log(O/H) = 8.65 \) for knot 3 using several independent empirical calibrations. This is the first gas-phase metallicity estimate reported for this galaxy.

NGC 4861

NGC 4861 is classified as a Magellanic irregular galaxy (Sandage & Tammann 1981) and a BCDG because of its blue colours and high UV continuum emission (French 1980; Thuan & Martin 1981). This object is located at a distance of 12.9 Mpc. NGC 4861 has a comet-like morphology (see Fig. 6), with many star-forming regions located along its major axis. The morphology of the galaxy was discussed by Dottori et al. (1994), who concluded that NGC 4861 might have undergone a merger process. From H I maps, this galaxy is an edge-on and rotating disc system (Conselice et al. 2000). Some authors have distinguished the bright star-forming region in the south (our knot 1) as NGC 4861 and the dwarf irregular galaxy IC 3961 (the rest of the galaxy) and recommended the definition of Mkn 59 to describe the full system. In any case, NGC 4861 has been amply studied as an example of a compact blue galaxy (e.g. Kobulnicky & Skillman 1998; Izotov et al. 1997; Izotov & Thuan 1999; Lee, Salzer & Melbourne 2004; Esteban et al. 2009).

Since the discovery of the broad He II \( \lambda 4686 \) emission line in the spectrum of this galaxy (Dinerstein & Shields 1986), many studies have confirmed the presence of WR stars in NGC 4861 (Schaefer et al. 1999). Broad C IV \( \lambda 5808 \) emission has also been detected in NGC 4861 (Izotov et al. 1997; Guseva et al. 2000). Our optical spectrum confirms the presence of these broad WR features. We derive WR/(WR+O) = 0.062 and WCE/WNL = 0.30, in agreement with previous estimates.

The most recent analysis of the ionized gas within this object was presented by Esteban et al. (2009), who derived an oxygen abundance of \( 12 + \log(O/H) = 8.05 \pm 0.04 \) using many nebular and auroral emission lines from optical spectra obtained with the 10-m Keck I telescope. Although slightly higher than the value we derive here using the emission lines observed in our optical spectrum.
The analysis of our Hα images allows us to quantify the star-formation activity throughout NGC 4861. The net-Hα image (Fig. 6) reveals 12 well-defined star-forming regions. The bright knot 1 hosts the majority of the starburst activity and, indeed, has the highest SFR per unit area. For this region we derive a SFR of 0.47 ± 0.03 M⊙ yr⁻¹ using the Hα luminosity. The SFR derived for all the galaxy is 0.48 ± 0.04 M⊙ yr⁻¹. The SFRs obtained from the available FIR and 1.4-GHz data are quite low (10–18 times lower) when compared with the Hα-based values, SFR$_{1.4GHz}$ = 0.086 M⊙ yr⁻¹ and SFR$_{1.4GHz}$ = 0.049 M⊙ yr⁻¹. As both the FIR and radio-continuum are tracing the star-formation activity in the last ∼100 Myr but the time-scale of the Hα emission is around 10 Myr, this may suggest that there has been an enhancement of the star-formation activity within this object in the last few million years.

The age of the most recent star-formation event in bright knot 1 is 4.6 Myr. Some knots seem to have even younger ages. The analysis of the broad-band optical colours suggests that the majority of the star-forming regions host important underlying stellar populations, with ages ranging from 30 to 100 Myr. This fact together with the presence of strong absorption features in the optical spectrum of the galaxy indicate the presence of an intermediate-age stellar population in this BCDG.

4.7 NGC 3003

NGC 3003 is a SBbc type galaxy located at 24 Mpc and appears to be almost edge-on (see Fig. 7). Its morphology shows two asymmetric spiral arms, suggesting that it may be a disturbed galaxy. Its southwest area shows a bright and compact region, which may be the remnant of a dwarf galaxy or just an intense H II region within the spiral arms of NGC 3003.

Ho, Filipenek & Sargent (1995) reported the presence of the broad blue WR bump in NGC 3003, and therefore the galaxy was included in the WR galaxy catalogue created by Schaerer et al. (1999). This feature has not been observed again in this galaxy. Indeed, it is not seen in our optical spectrum; however, it has a low S/N. Using the brightest emission lines and typical empirical calibrations we derive an oxygen abundance of $12 + \log(O/H) = 8.57$ for this galaxy. Although NGC 3003 has been well studied in the past, we have not found any previous estimation of its gas-phase metallicity in the literature.

Our net-Hα image allows us to identify 25 independent star-forming regions, including the bright nucleus (knot 13) and the intriguing bright object in the south-west (knot 3). These two knots actually host the highest Hα emission of the galaxy. The total Hα luminosity of NGC 3003, adding up the flux of all star-forming region, is $2.97 \times 10^{40}$ erg s⁻¹, which can be translated into a total SFR of 0.24 M⊙ yr⁻¹. Our derived Hα luminosity is four times lower than that derived by Hoopes, Walterbos & Rand (1999), who reported $L_{Hα} = 1.18 \times 10^{41}$ erg s⁻¹. Some part of the missing Hα flux may be a consequence of not considering an adequate value for the correction for extinction, which may be important in edge-on galaxies. However, we should also expect that there is some diffuse Hα gas in the galaxy that does not belong to the analysed regions and hence it was not considered in our total flux. The SFRs derived from the FIR and radio-continuum data available for this galaxy are SFR$_{60μm}$ = 0.39 M⊙ yr⁻¹, SFR$_{FIR}$ = 0.15 M⊙ yr⁻¹, and SFR$_{1.4GHz}$ = 0.58 M⊙ yr⁻¹. All these values suggest that the total Hα luminosity computed by Hoopes et al. (1999), which translates into a SFR of 0.94 M⊙ yr⁻¹, is probably a slight overestimate.

We estimated the age of the most recent star-formation event via the Hα equivalent width and the $U - B$ colours, finding typical values between 3 and 6 Myr. The optical colours obtained for the star-forming regions, in particular the $V - R$ and the $V - I$ colours, clearly indicate the presence of an important old stellar population underlying the bursts, with ages in many cases older than 500 Myr. Indeed, this is the only galaxy for which we find ages higher than 1 Gyr in some knots.

6 SUMMARY AND CONCLUSIONS

We have presented a detailed photometric and spectroscopic study of a sample of seven Wolf–Rayet galaxies. The observed galaxies are NGC 1140, IRAS 07164+5301, NGC 3738, UM 311, NGC 6764, NGC 4861 and NGC 3003. Star-forming regions within these galaxies have been identified using narrow-band Hα images. By combining these images with the data obtained using our optical broad-band images, we analysed the morphologies, colours, star-formation rates and stellar populations of these star-forming regions.

We discussed the morphology of the galaxies using our broad-band images. In some cases (NGC 1140, UM 311, NGC 481 and NGC 3003), we found features that may indicate that the galaxy has experienced a recent interaction.

We used the Hα images and optical broad-band colours in combination with Starbursts99 models to derive the ages of the most recent star-formation events. We confirmed that almost all the analysed regions show a very young (3–6 Myr old) starburst. We also used the optical colours to estimate the internal reddening and to study the age of the dominant underlying stellar populations within all these regions. Knots in NGC 3738, 6764 and 3003 generally show the presence of an important old (400–1000 Myr) stellar population. However, the optical colours cannot be used to detect stars older than 20–50 Myr in the knots of the other four galaxies. This fact suggests that both the current intensity of the starbursts and the star-formation activity has been ongoing for at least a few tens of millions of years in these objects. Deep NIR data is needed to detect the old stellar populations in these galaxies.

We derived the SFR of each knot using the Hα luminosity. The Hα-based SFR derived for each galaxy usually agrees well with the SFR derived using FIR and radio-continuum data.

The optical spectra were used to search for the faint WR features, to confirm that the ionization of the gas is a consequence of the massive stars, and to quantify the chemical properties of each object. The high S/N optical spectrum of NGC 1140 and 4861 allowed us to obtain a precise estimate of the oxygen abundance of the ionized gas using the direct method (i.e. via the detection of the faint [O III] λ4363 emission line). We also derived the chemical abundances of N, S, Ne and Ar in these two galaxies. In NGC 4861, the N/O ratio is ∼0.25–0.35 dex higher than that expected from its oxygen abundance. This fact may be related to the presence of WR stars within this galaxy. Indeed, we clearly detected features originating in WR stars in NGC 1140 and 4861 and used them to derive the population of O, WNL and WCE stars. In both cases, the derived WR/(WR + O) and WCE/WNL ratios agree well with those expected for galaxies with similar oxygen abundances.

For the rest of the galaxies we provided estimates of the oxygen abundance of the ionized gas using several independent empirical calibrations. We have presented the first oxygen abundances computed for NGC 6764 and 3003, namely $12 + \log(O/H) = 8.65$.
and 8.57, respectively. We also derived the oxygen abundance of IRAS 07164+5301, namely $12 + \log(O/H) = 8.50$, which is $\sim$34 percent of the only available determination of the metallicity of this galaxy.

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