Optical spectroscopy of star-forming regions in dwarf Wolf–Rayet galaxies

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ABSTRACT

We present here spatially resolved optical spectroscopic observations of four nearby dwarf Wolf–Rayet (WR) galaxies. The ages of the most recent starburst events in these galaxies are found between 3 and 10 Myr. The gas-phase metallicities \([12+\log(O/H)]\) for the spatially resolved star-forming regions are derived using several indicators. The star-forming regions within the galaxies are found chemically homogeneous within the uncertainties in the estimates. Nitrogen-enrichment as expected in the WR regions is not detected. This implies that metal-enrichment due to supernovae explosions in the most recent star-forming episode is not being detected here. It is suggested that the newly synthesized metals still reside in hot gas-phase. The metals from the previous episodes, cooled by now and well mixed across the whole extent of galaxies, are making galaxies chemically homogeneous with normal nitrogen-to-oxygen ratio. These galaxies are residing in dense environments with galaxy density in the range of \(8–80\, \text{Mpc}^{-3}\).

Key words: galaxies: starburst – galaxies: dwarf – galaxies: abundances – galaxies: ISM – stars: Wolf–Rayet.

1 INTRODUCTION

Dwarf galaxies are ubiquitous in the local Universe. About 80–90 percent members of the local group (Mateo 1998; Grebel 2001a) and about 80 percent of the known galaxies in the local volume (\(D \leq 10\, \text{Mpc}\); Karachentsev et al. 2004) are classified as dwarf galaxies. Dwarf galaxies are generally defined based on their absolute magnitude \(M_B \gtrsim -16\, \text{mag}\) (Tammann 1994) or \(M_V \gtrsim -18\, \text{mag}\) (Grebel 2001a,b). Their space density in the Universe is about 40 times that of the brighter galaxies (Staveley-Smith et al. 1999; Kunth & Östlin 2000; Kniazev et al. 2004; Papaderos et al. 1999; Izotov et al. 2008). Dwarf galaxies usually have low stellar-mass (\(<10^{10}\, \text{M}_\odot\)), low luminosity (\(<10^{10}\, \text{M}_\odot\)), high gas content (\(M_{HI} \gtrsim 10^9\, \text{M}_\odot\)), and low metallicity between 7.0 and 8.4 (Searle & Sargent 1972; Izotov et al. 1999; Kunth & Östlin 2000; Kniazev et al. 2004; Papaderos et al. 2008). Dwarf galaxies play an important role in the formation and evolution of galaxies. In hierarchical models of galaxy growth, larger structures like giant spiral and massive elliptical galaxies form through mergers and accretion of smaller structures like dwarf galaxies (e.g. White & Frenk 1991; Kauffmann, Nusser & Steinmetz 1997; Shlosman 2013; Amorisco, Evans & van de Ven 2014; Deason, Wetzel & Garrison-Kimmel 2014).

Dwarf galaxies are further classified as irregulars (dIs), dwarf ellipticals (dEs), dwarf spheroidals (dSphs), dwarf spirals (dSs), and blue compact dwarfs (BCDs) based on their optical appearances. Several possibilities of evolutionary connections between different types of dwarf galaxies have been proposed; however, this issue is not completely resolved (Thuan 1985; Davies & Phillipps 1988; Drinkwater & Hardy 1991; James 1994; Papaderos et al. 1996). Among these sub-types, BCDs appear extremely blue due to recent starburst activity in a compact (<1 kpc) region (Zwicky 1965; Thuan & Martin 1981). Since starburst activity in BCDs takes place within an underlying old stellar population; therefore, BCDs may not be considered young systems (e.g. Loose & Thuan 1986; Krueger, Fritz-v. Alvensleben & Loose 1995; Papaderos et al. 1996; Bergvall & Östlin 2002; Noeske et al. 2003; Caon et al. 2005; Gil de Paz & Madore 2005; Zhao, Gao & Gu 2013). The very young (<10 Myr) stellar population dominated by O/B type stars in the star-bursting regions give blue colors to these galaxies. Their optical spectra are dominated by strong emission lines attributed to the ongoing star formation. BCDs were once considered equivalent to the primeval galaxies undergoing their first episode of star formation in the presence of nearly pristine interstellar medium (ISM; Sargent & Searle 1970). The issue as to whether BCDs exhibit old stellar populations or not has been widely explored for several years (e.g. Sargent & Searle 1970; Searle, Sargent & Bagnuolo 1973; Izotov & Thuan 1999, 2004; Aloisi et al. 2005). Majority of BCDs have been found to have an underlying old stellar population with ages between 1 and 10 Gyr. These studies also indicated that the starburst activities in BCDs do not last longer than about a few tens of Myr. The star formation in BCDs is inferred episodic with intense star formation activities separated by a relatively long phase of quiescence (Thuan et al. 1991; Krueger et al. 1995; Mas-Hesse & Kunth 1999; Thornley et al. 2000). Very few H I -selected dwarf galaxies...
in the quiescent phase without Hα emission have been seen with non-zero star formation rate (SFR; van Zee 2001; Lee et al. 2009), which implies that dwarf galaxies also maintain a low level of star formation activities over long periods.

BCDs show intense star-forming activity, fed by a relatively large amount of gas (Thuan & Martin 1981; Staveley-Smith, Davies & Kimman 1992; van Zee, Skillman & Salzer 1998). Ultimately, the formation of young massive stars (≥8−10 M⊙) and their subsequent evolutions cause the fresh metals (oxygen and other α elements) ejection into the ISM via stellar winds and supernova explosions. The released metals will be dispersed and mixed with the ISM via hydrodynamical process in timescales of a few 100 Myr (e.g. Roy & Kuntz 1995; Tenorio-Tagle 1996). This implies that the spatial distribution of the metal abundances in galaxies is a function of the recycling and mixing time scales of the ISM. The spatially resolved abundance analysis in galaxies can therefore provide important insights about the chemical evolution of galaxies. These issues have been addressed by studying the spatial distribution of optical emission line ratio and of certain elemental abundances in dwarf galaxies (e.g. Walsh & Roy 1989; Kobulnicky & Skillman 1996; Kobulnicky et al. 1997; Lee, Skillman & Venn 2006).

Some studies have revealed spatial variations in the chemical compositions as measured from the gas-phase metallicity in different types of dwarf galaxies. For example, a shallow gradient (≥0.11 dex kpc−1) in metallicity was inferred in SBS 0335-052E (Paspaderos et al. 2006). Inhomogeneous metallicity has been seen in extremely metal-poor galaxies, where it was noticed that the low metallicity regions are normally associated with intense star-forming regions (Paspaderos et al. 2006; Izotov & Thuan 2009; Levesque et al. 2011). The existence of significantly large metallicity gradient or inhomogeneity within the galaxies is often understood in terms of a recent merger of two galaxies with different metallicities and tidal interactions (López-Sánchez, Esteban & Rodríguez 2004b,a; López-Sánchez & Esteban 2009, 2010b; Paswan, Omar & Jaiswal 2018). It may be noted here that typical metallicity gradients between −0.009 and −0.231 dex kpc−1 are common in large spiral galaxies (Zaritsky, Kennicutt & Huchra 1994).

On the other hand, a good number of studies have also indicated that BCD galaxies have homogeneous chemical abundances (Kobulnicky & Skillman 1996; Papaderos et al. 2006; Kehrig et al. 2008; Cairós et al. 2009; Pérez-Montero & Contini 2009; Hägele et al. 2011; Pérez-Montero et al. 2011; Lagos & Papaderos 2013). The chemical homogeneity in galaxies is explained as a consequence of starburst-driven feedback that disperses and mixes the newly synthesized elements in the ISM through hydrodynamical processes (Tenorio-Tagle 1996). An issue related to metallicity is also the nitrogen-to-oxygen (N/O) ratio, which is observed to be increasing at high metallicities albeit with a large scatter. The production of nitrogen and oxygen and its subsequent maintenance in the gas phase in the ISM is not completely understood. Massive stars produce small amounts of nitrogen in early phase of evolution, which is termed as the primary production of nitrogen (Edmunds & Pagel 1978; Allsion et al. 1979; Izotov & Thuan 1999). Low and intermediate mass stars produce nitrogen and other elements heavily enriching ISM with a significant time lag from the primary production time-scales. This latter process is often termed as the secondary production. The low metallicity regions (12 + log(O/H) ≤ 7.8) with a constant N/O ratio around ~1.6 is believed to be primarily due to primary production of nitrogen in massive stars. At high metallicity, a steep increase in N/O ratio is observed, which is due to increased secondary production and partly also due to selective depletion of oxygen in dust grains (Henry, Edmunds & Köpken 2000; Izotov et al. 2006; Brinchmann, Kuntz & Durrett 2008; Pérez-Montero & Contini 2009; López-Sánchez & Esteban 2010b; Belfiore et al. 2015; Vincenzo et al. 2016). The mixing of recently produced metals with the surrounding ISM can also modify the observed N/O ratio.

In this paper, we present slit-based optical spectroscopic observations of spatially resolved star-forming regions in four dwarf galaxies. These galaxies are taken from the galaxy catalogue made by Brinchmann et al. (2008), in which these galaxies are classified as Wolf–Rayet (WR) galaxies based on detection of broad emission line features in the optical spectrum from the Sloan Digital Sky Survey (SDSS) data release 6 (DR6). The WR galaxies are a subset of star-bursting H II emission-line galaxies, which show high ionization emission line of He II λ4686 in their optical spectra along with two broad features around He II λλ4686 and C IV λλ5808 emission lines known as the blue bump and the red bump, respectively (Allen, Wright & Goss 1976; Osterbrock & Cohen 1982; Conti 1991). The WR phase in a galaxy is a strong indicator of an ongoing young starburst (<10 Myr) activity, as the most massive O/B-type stars come in to the WR phase after 2–5 Myr from their birth before they end this phase through supernovae explosions in a very short time of <0.5 Myr (Meynet & Maeder 2005). While the SDSS optical spectra for the selected WR galaxies are already available, we re-observed these galaxies due to the following reasons: (a) the SDSS spectrum has the wavelength coverage of 3800–9200 Å, which missed the emission line [O II] λλ3727 for low-z galaxies, required for obtaining a direct estimate for the oxygen abundance, (b) galaxies in our sample contain multiple star-forming regions, and the SDSS spectra were obtained at a single location often coinciding with the brightest H II region. The general properties of the sample galaxies are provided in Table 1. These WR dwarf galaxies were previously studied by Jaiswal & Omar (2016) using the deep Hα and SDSS r-band imaging. We present here physical and chemical properties of spatially resolved star-forming regions in these galaxies.

2 OBSERVATIONS AND DATA REDUCTION

The Faint Object Spectrograph and Camera (FOSC) mounted on the 2-m Himalayan Chandra Telescope (HCT) of the Indian Astronomical Observatory (IAO), Hanle, India, was used to carry out optical spectroscopic observations. The HCT FOSC is equipped with a 2k × 4k SITE CCD chip, which uses the central 2k × 2k region with a plate scale of 0.296 arcsec pixel−1 for spectroscopic observations. The gain and readout noise of the CCD camera are 1.22 e− ADU−1 and 4.87 e−, respectively. The spectroscopic observations of the selected dwarf WR galaxies in our sample were obtained with a slit of aperture 1.92 arcsec × 11 arcmin and a grism providing a spectral resolution of ~1300. The spectrum covers the wavelength range from ~3500 Å to ~7500 Å with a dispersion of ~1.5 Å pixel−1 and an effective spectral resolution of ~11 Å. The seeing FWHM (full width at half-maximum) was in the range of 1.5–2.2 arcsec with an average value of ~2 arcsec. In our observations, the slit position was located in such a way that it covered multiple H II regions in a galaxy. The slit orientations for each galaxy are shown in Fig. 1. The Fe-Ar lamp exposures were used for the wavelength calibration of the spectrum. The absolute flux calibration was achieved by observing spectrophotometric standard star Feige 34 selected from Oke (1990). The observational details for the target sources in our sample are provided in Table 2.
Table 1. General properties of the galaxies in the present sample.

| Galaxy name | RA (J2000) [h:m:s] | Dec (J2000) [d:m:s] | Type | Distance [Mpc] | \( V_{\text{helio}} \) [km s\(^{-1}\)] | \( M_B \) [mag] | Optical size [arcmin × arcmin] | Other name |
|-------------|---------------------|---------------------|------|---------------|-----------------|----------|-----------------------------|------------|
| IC 3521     | 12 34 39.5          | +07 09 37           | IBm  | 12.7          | 595             | −16.7    | 1.43 × 0.93                 | UGC 7736   |
| CGCG 038-051| 10 55 39.2          | +02 23 45           | dIrr | 19.0          | 1021            | −15.0    | 0.57 × 0.26                 | —          |
| CGCG 041-023| 12 01 44.3          | +05 49 17           | SB   | 23.3          | 1350            | −16.7    | 0.72 × 0.53                 | VV 462     |
| SBS 1222+614| 12 25 05.4          | +01 09 11           | dIrr | 11.4          | 706             | −14.6    | 0.51 × 0.43                 | —          |

Figure 1. The colour composite image made using g-, r-, and i-band images taken from the SDSS survey. The slit positions in the HCT observations are overlaid on the images. The spatially resolved HII regions (blue regions) are also labeled over which the spectra are extracted.

Table 2. Summary of the optical spectroscopic observations.

| Galaxy name | Date         | Exposure time [min] | Airmass |
|-------------|--------------|---------------------|---------|
| IC 3521     | 2016 Dec 2   | 20                  | 1.3     |
| CGCG 038-051| 2016 Dec 2   | 60                  | 1.4     |
| CGCG 041-023| 2016 Dec 1   | 60                  | 2.1     |
| SBS 1222+614| 2013 May 12  | 30                  | 1.4     |

The spectroscopic data reduction was performed using the standard procedures in the IRAF (Image Reduction and Analysis Facility). Bias-subtraction and flat-fielding were applied on each frame. Cosmic ray removal was done using the Laplacian kernel detection algorithm (van Dokkum 2001). Extraction of one-dimensional spectra based on optimal extraction algorithm by Horne (1986) was carried out. This algorithm provides the optimal signal-to-noise ratio (SNR). The aperture adopted by the extraction algorithm is subjected to non-uniform pixel weights with lower weights to pixels that are far from the central peak of the spatial profile and receive less light from the target source. The fluxes for the emission lines were measured with the SPLT task of the IRAF by directly summing the flux under the line. This task takes care of the proper subtraction of underlying local continuum flux. Similarly, the line equivalent widths (EWs) were measured in a standard way by dividing emission line flux with its corresponding underlying local continuum flux. The errors in the line flux measurements were estimated using \( \text{rms} \times \sqrt{2 \times N} \), where \( N \) is the number of pixels covered in the Gaussian profile of the emission line. The \( \text{rms} \) was estimated from the line-free region (continuum) on both sides of the emission line.

3 RESULTS AND ANALYSIS

The star-forming regions in dwarf WR galaxies studied here were previously identified from the continuum subtracted Hα image taken with the 1.3-m Devasthal Fast Optical Telescope (DFOT; Jaiswal &
These H II regions appear blue in color composite images made using the SDSS g-, r-, and i-band images as shown in Fig. 1. The Hα emission profiles and the size of the apertures over which the spectra corresponding to the locations of spatially resolved H II regions were extracted, are shown in Fig. 2. Several distinct H II regions having different angular extents can be identified in these images. The optical one-dimensional spectra were extracted over different extraction apertures so as to cover most of the bright blue-emitting regions in the galaxies. The sizes of the extraction apertures used here vary from ~6 × 1.92 arcsec to ~14 × 1.92 arcsec, depending on the extent of the emission regions. The minimum aperture of ~6 arcsec corresponds to nearly three times the observed average seeing FWHM. The extinction corrected calibrated spectra in the rest-frame are shown in Figs 3–6. The calibrated spectra for each H II region were dereddened for galactic and internal extinction using the reddening law of Cardelli, Clayton & Mathis (1989) with a total-to-selective extinction ratio of $R_V = 3.1$. The spectra were first corrected for the Galactic extinction using the reddening value of $E(B - V)_\text{Galactic}$ in the direction of the galaxies estimated from Schlafly & Finkbeiner (2011) recalibration of the Schlegel, Finkbeiner & Davis (1998) infrared-based dust map, as implemented in NASA/IPAC Extragalactic Database (NED). Thereafter, the Galactic extinction corrected spectra were corrected for internal extinction using the flux ratio of $f_{\text{H}\alpha}/f_{\text{H}\beta}$ lines by assuming the expected theoretical value as 2.86 and the Case-B recombination (Osterbrock & Bochkarev 1989; Kong & Cheng 2002) with an electron temperature of ~10^4 K and electron density of 100 cm$^{-3}$. The estimated values of the Galactic reddening $E(B - V)_\text{Galactic}$ and internal reddening $E(B - V)_\text{internal}$ are provided in Table 3. In some cases, the flux ratio of $f_{\text{H}\alpha}/f_{\text{H}\beta}$ lines was found less than the expected theoretical value of 2.86. A low value of $f_{\text{H}\alpha}/f_{\text{H}\beta}$ is often associated with intrinsically low reddening and hence we assumed a $E(B - V)_\text{internal}$ as zero for such cases. Previously, lower than theoretical value of $f_{\text{H}\alpha}/f_{\text{H}\beta}$ has been reported in several galaxies (López-Sánchez & Esteban 2009; Ramya, Sahu & Prabhu 2009; Gunawardhana et al. 2013; Paswan et al. 2018). Such a low value is usually believed as resulted from variations in physical conditions of ionized gas such as high electron temperature or low electron density in the emission region for which the theoretical ratio $f_{\text{H}\alpha}/f_{\text{H}\beta}$ may be less than 2.86 (e.g. Grinin 1980; López-Sánchez & Esteban 2009). A low value may also result due to error in the line flux calibration and measurement (Kewley et al. 2006). The spectrum from the central region of IC 3521 shows weak Hα line in absorption and no emission line. Therefore, the central region of IC 3521 was not included in further analysis. The spectra for the knot #a in IC 3521 and knots #b and #c in CGCG 041-023 have no or weak detection of the Hβ line although the Hα and [N II] λ6584 lines were clearly detected. Therefore, these spectra could not be corrected for internal extinction.

The observations of CGCG 041-023 were performed at relatively high airmass of 2.1, where slit-light losses due to differential atmospheric refraction become significant. The slit-light losses
are expected to be higher towards the bluer wavelengths. The position angle (≈ 70°) of the slit orientation in this case was close to the parallactic angle (≈ 60°). We also found that after applying the Galactic extinction correction, the flux ratio of $f_{H\alpha}/f_{H\beta}$ for the knot #a in CGCG 041-023 is ≈ 2.71 which is slightly less than the expected theoretical value of 2.86. If slit-light losses near the $H\beta$ line were significant, the apparent $f_{H\alpha}/f_{H\beta}$ ratio is supposed to increase from the theoretical value. This suggests that the light losses due to differential atmospheric refraction are not significant.

The prominent emission lines were identified and marked in the spectra. These lines include the Balmer lines of Hydrogen $H\beta$, $H\gamma$, $H\alpha$, He II $\lambda$4686 and numerous forbidden emission lines such as [O II] $\lambda$3726, [O III] $\lambda$$\lambda$4363 and [O III] $\lambda$4959, 5007, [N II] $\lambda$6584, [S II] $\lambda$$\lambda$6717, 6731 and some other emission lines such as [Ne III] $\lambda$3868, 3967 and [Ar III] $\lambda$7136. The flux values obtained for the lines along with EWs of the $H\alpha$, $H\beta$ and [O III] $\lambda$5007 lines for the H II regions in the galaxies are given in Table 3. It is known that more than ≈ 90 per cent contribution to the emission from the H II regions in BCDs is due to ongoing young burst of star formation (Papaderos et al. 1996; Noeske, Papaderos & Fricke 1999; Cairós et al. 2001; Amorín et al. 2009). Normally, the Balmer absorption EWs are found < 3 Å (González Delgado, Leitherer & Heckman 1999) in star-forming galaxies, which is insignificant compared to the uncertainty in our estimates for the emission line EWs. Therefore, the Balmer emission line EWs are not corrected here for a relatively weak absorption EW due to old stellar population underlying in the emission region.

### 3.1 Age of the recent starburst

The age of the most recent star formation can be predicted from the $H\alpha$ and $H\beta$ line EWs as the EW decreases with time in a well-defined manner (Leitherer et al. 1995; Johnson & Conti 2000). We used the Starburst99 model provided by Leitherer et al. (1999) to estimate the age of the most recent star formation event in our sample of dwarf WR galaxies. The Padova stellar evolutionary model with asymptotic giant branch (AGB) evolution was fitted to obtain EW track of the starburst, assuming the Salpeter initial mass function (IMF) with lower and upper stellar mass limits as 0.1 $M_\odot$ and 100 $M_\odot$, respectively. This model uses instantaneous star formation scenario. The metallicity input to the model was provided from the
estimates made using direct $T_e$-method. For the H II regions where
direct estimates of metallicities were not available, the metallici-
ties estimated from empirical calibration based on photoionization
models given by Pettini & Pagel (2004) were used. The details of
the metallicity estimations are presented in Section 3.5. The EW
tracks for the Hα and Hβ lines for all spatially resolved H II regions
were obtained. The age of the star formation was then estimated
by comparing the observed EWs of the Hα and Hβ lines to that
obtained from the model track. A comparison of the star formation
age estimated from the Hα and Hβ EWs is shown in Fig. 7. This
figure suggests that the estimated ages using the observed EWs of
the Hα and Hβ lines are in good agreement with each other within
about ± 2 Myr. We adopted age of the most recent star formation
as the mean of the ages estimated from EWs of the Hα and Hβ
lines. These ages for the star-forming regions are given in Table 3.
We found that the age of the most recent starburst in our sample of
dwarf WR galaxies is younger than ∼6 Myr, except for the regions
‘b’ and ‘c’ in CGCG 038-051 and for the region ‘b’ in CGCG 041-
023, which have ages as 8 ± 1, 10.8 ± 1.1, and 9 ± 1 Myr old,
respectively.

3.2 Detection of the WR features
The broad blue WR bump feature around 4686 Å was searched in
all the star-forming regions in the galaxies. A clear detection of the
broad blue WR bump was made only in two star-forming regions
hosted by SBS 1222+614 as shown in Fig. 8. This detection is in
good agreement with Shirazi & Brinchmann (2012), who have also
reported the WR features in SBS 1222+614. The broad blue bump
consists of a blend of C III/C IV $\lambda 4650$, 4658, N III $\lambda 4634$, 4640,
[Ar IV] $\lambda 4711$, 4740, and He II $\lambda 4686$ emission lines. This detection
generally indicates a good number ($10^2$–$10^5$) of young WR stars
in the galaxy (e.g. Kunth & Sargent 1981; Kunth & Schild 1986).
The blue bump appears mainly due to the presence of late-type
WN (WNL) and early-type WC (WCE) stars (Schaerer & Vacca
1998). The red WR bump around 5808 Å is also expected in the
WR galaxies. We also possibly identified the red bump feature in
the SBS 1222+614 (# a + b) region as shown in Fig. 9. The red WR bump appears mainly due to the presence of emission lines
[N II] $\lambda 5795$ and He I $\lambda 5875$ from the WCE stars. The red bump is
rarely detected in WR galaxies as it contains very weak emission

Figure 4. The rest-frame extinction-corrected optical spectra of the spatially resolved H II regions in dwarf WR galaxy CGCG 038-051, observed with the
2-m HCT.
line and is expected in high-metallicity region (Guseva, Izotov & Thuan 2000). Although we could not detect the WR features in the star-forming regions of other galaxies in our sample, the optical SDSS spectrum for the brightest regions of knot #b and #a in IC 3521 and CGCG 041-023, respectively, shows a detection of WR features (Brinchmann et al. 2008). The SDSS spectrum also shows the detection of the broad WR blue bump having a relatively lower strength in the knot #b of CGCG 038-051. These detections are missed out in this study most likely due to the low SNR in the blue part of the spectra. The starburst ages estimated to be very young (≤6 Myr; see Table 3) for these star-forming regions including those present in SBS 1222+614 are consistent with the detection of the WR features, which appears only during the very early periods of star formation. Although a few other star-forming regions such as the knot #a in IC 3521 and CGCG 038-051 and knot #c in CGCG 041-023 showing a very young starburst of ≤6 Myr are expected to have the WR features, it is not clear from the present data if these regions also host WR stars or not. Some star-forming regions such as knot #c and b in CGCG 038-051 and CGCG 041-023, respectively, show the starburst of ages of ~10 Myr, indicating that they have probably completed their WR phases. Overall, the detections of the WR features from our own observations and those from the SDSS data from at least one star-forming region in each galaxy in the sample suggest that the sample galaxies are undergoing young massive star formation phase having a significant population of WR stars.

3.3 Ionization mechanism

The detection of high ionization emission lines of He II λ4686, [O III] λ4363, [O III] λ4959, 5007, and [Ar III] λ7135 and low ionization emission lines of [O II] λ3726, [N II] λ6584 and [S II] λ6717, 6731 etc., in the galaxy spectrum can be an indication of mix of many excitation sources such as photoionization mainly from massive ionizing stars and shocks generated by WR stars, supernovae explosions, and energetic active galactic nuclei-related mechanisms as discussed by Garnett et al. (1991), Garnett, Kennicutt & Bresolin (2004), Guseva et al. (2000), and López-Sánchez & Esteban (2010a). Therefore,
it is necessary to identify the dominant excitation mechanism in these galaxies. The nature of the dominant ionizing source can be inferred using the quantitative classification scheme proposed by Baldwin, Phillips & Terlevich (1981) using combinations of line ratios. Subsequently, other similar diagnostic schemes were proposed by Dopita et al. (2000) and Kewley et al. (2001). All these diagnostic schemes use the emission line ratios of \([\text{O III}]\, \lambda 5007/\text{H} \beta\), \([\text{N II}]\, \lambda 6583/\text{H} \alpha\) and \([\text{S II}]\, \lambda 6717, 6731/\text{H} \alpha\). The optical emission line ratios for all the spatially resolved ionized regions in our galaxy sample are listed in Table 3 and the locations of all the star-forming regions are presented in Fig. 10, which shows typical plots for \([\text{O III}]\, \lambda 5007/\text{H} \beta\) versus \([\text{N II}]\, \lambda 6583/\text{H} \alpha\) (top panel) and \([\text{O III}]\, \lambda 5007/\text{H} \beta\) versus \([\text{S II}]\, \lambda 6717, 6731/\text{H} \alpha\) (bottom panel). Here, we used the latest Kewley et al. (2001) diagnostic criteria to identify source of excitation mechanism. In these figures, it can be seen that the primary and dominating source of ionization is photoionization in all the cases.

3.4 Physical conditions of the ionized gas

The electron temperature (\(T_e\)) and density (\(n_e\)) of the ionized gas in the H II regions are estimated here. Since the faint auroral \([\text{O III}]\, \lambda 4363\) emission line along with the \([\text{O III}]\, \lambda 4959, 5007\) emission lines were detected in many cases, the electron temperature could be estimated directly using their relative line intensities. A two-zone approximation was assumed to estimate \(T_e\) for the ionized regions, where \(T_{e, \text{[O III]}}\) and \(T_{e, \text{[O II]}}\) were taken as representative temperatures for high and low ionization potential ions, respectively. We inferred \(T_{e, \text{[O III]}}\) from the diagnostic line ratio of \([\text{O III}]\, I(\lambda 4959 + \lambda 5007)/I(\lambda 4363)\) by using the five-level program within the NEBULAR task of the IRAF for the emission line nebulae (Shaw & Dufour 1995). Once \(T_{e, \text{[O III]}}\) was estimated, \(T_{e, \text{[O II]}}\) was inferred using the linear relation between \(T_{e, \text{[O III]}}\) and \(T_{e, \text{[O II]}}\) (Garnett 1992). The values of \(T_{e, \text{[O III]}}\) and \(T_{e, \text{[O II]}}\) estimated for the star-forming regions are given in Table 4. These derived temperatures are in good agreement with those measured in other nearby star-forming dwarf galaxies (e.g. Campbell, Terlevich & Melnick 1986; Masegosa, Moles & Campos-Aguilar 1994; Lee, Salzer & Melbourne 2004; Häger et al. 2008). In order to measure the electron density of the ionized gas, the diagnostic line ratio of the doublet \([\text{S II}]\, I(\lambda 6717)/I(\lambda 6731)\) was used. Since these two lines of the same ion are emitted from different levels with nearly same excitation energy, the electron density can be estimated using this line ratio. The computed electron densities are listed in Table 4.

3.5 Oxygen abundance

We derived the ionic oxygen abundance through electron temperature-sensitive lines such as \([\text{O III}]\, \lambda 4363\) and \([\text{O III}]\, \lambda 4959, 5007\) using \(T_e\)-method as expressed in Izotov et al. (2006). Since this method uses the electron temperature-sensitive emission line of oxygen \([\text{O III}]\, \lambda 4363\) (Kennicutt, Bresolin & Garnett 2003) which is often very weak and difficult to detect in galaxies, the estimation of ionic oxygen abundance could be made for 5 out of 10 spatially resolved H II regions in the galaxies. The estimated ionic oxygen abundances using \(T_e\)-method are given in Table 4. This method assumes two zone approximation: a high-ionization zone represented with the temperature \(T_{e, \text{[O III]}}\), responsible for \([\text{O III}]\) lines; and a low-ionization zone represented with the temperature \(T_{e, \text{[O II]}}\), responsible for \([\text{O II}]\) lines. The two-zone approximation model for \(T_e\) is more realistic interpretation of the temperature structure within the H II regions and provides more accurate estimates of ionic oxygen abundances (Pilyugin 2001). The total oxygen abundance is then determined by performing a simple sum of \([\text{O II}]\) and \([\text{O III}]\) emission lines as follows (e.g. Pagel et al. 1992; Shi et al. 2005;
Table 3. The dereddened optical emission line flux, equivalent width, starburst age, and other parameters for the spatially resolved star-forming regions in dwarf WR galaxies.

| Galaxy | IC 3521 (knot #a) | IC 3521 (knot #b) | CGCG 038-051 (knot #a) | CGCG 038-051 (knot #b) | CGCG 038-051 (knot #c) |
|--------|-------------------|-------------------|------------------------|------------------------|------------------------|
|        | Wavelength [Å]    | Flux [10^{-14} erg s^{-1} cm^{-2}] | Flux [10^{-14} erg s^{-1} cm^{-2}] | Flux [10^{-14} erg s^{-1} cm^{-2}] | Flux [10^{-14} erg s^{-1} cm^{-2}] |
| O II   | 3726              | 0.69 ± 0.04       | 0.86 ± 0.03             | –                      | –                      |
| Hα     | 6563              | 6.21 ± 0.05       | 10.20 ± 0.04            | 7.50 ± 0.02            | 4.55 ± 0.01            | 1.79 ± 0.02            |
| N II   | 5568              | 1.92 ± 0.05       | 2.86 ± 0.04             | 0.17 ± 0.01            | 0.12 ± 0.01            | –                      |
| S II   | 6717              | 0.81 ± 0.04       | 1.27 ± 0.05             | 0.28 ± 0.01            | 0.24 ± 0.01            | 0.09 ± 0.02            |
| S II   | 6731              | 0.54 ± 0.03       | 1.06 ± 0.04             | 0.20 ± 0.01            | 0.23 ± 0.01            | 0.03 ± 0.01            |
| Ar III | 7135              | –                 | –                      | 0.14 ± 0.01            | 0.10 ± 0.01            | 0.03 ± 0.01            |
| E(B − V)_{foreground} | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 |
| E(B − V)_{internal} | 0 | 0.19 ± 0.04 | 0.15 ± 0.01 | 0 | 0.58 ± 0.09 |
| M_B   | −12.07 ± 0.16     | −9.01 ± 0.16      | −12.20 ± 0.15           | −14.88 ± 0.15          | −10.66 ± 0.15          |
| μ − r | 0.23 ± 0.01       | 1.69 ± 0.14       | 0.40 ± 0.04             | 0.86 ± 0.02            | 0.13 ± 0.11            |
| Log (M_{stellar}) | 6.95 | 7.21 | 6.12 | 7.89 | 6.67 |
| [M/O] | 525 ± 109         | 369 ± 27          | 767 ± 60                | 491 ± 34               | 485 ± 82               |
| − EW (Hα) [Å] | 30 ± 2 | 139 ± 10 | 117 ± 13 | 18 ± 3 | 18 ± 3 |
| − EW | 643 ± 51          | 575 ± 45          | 59 ± 9                  |
| (O III)]A5007) [Å] | – | – | 0.63 ± 0.01 | 0.66 ± 0.01 | 0.40 ± 0.06 |
| Log [N II] | −0.51 ± 0.01 | −0.55 ± 0.01 | −1.64 ± 0.03 | −1.58 ± 0.04 | – |
| Log [S II]_6717, 6731/Hα | −0.66 ± 0.08 | −0.64 ± 0.01 | −1.19 ± 0.01 | −1.00 ± 0.01 | −1.15 ± 0.08 |
| p−parameter | – | – | 0.82 ± 0.02 | 0.85 ± 0.03 | – |
| b−parameter | – | – | 6.92 ± 0.16 | 7.24 ± 0.18 | – |
| R−parameter | – | – | 5.67 ± 0.07 | 6.18 ± 0.12 | – |
| Age [Myr] | 4.01 ± 0.48 | 5.31 ± 0.04 | 6.61 ± 0.16 | 8.01 ± 0.26 | 10.74 ± 0.29 |

Note. a,b,c: These parameters are defined in Section 3.5.

Oxygen abundances corresponding to the H II regions are also determined using different methods such as N2, O3N2, and P-methods, which are empirically calibrated based on the photoionization models (Pilyugin 2001; Denicoló, Terlevich & Terlevich 2002; Pettini & Pagel 2004). These empirical methods allow to estimate oxygen abundances where the detection of [O III] λ4363 emission line is not made. The oxygen abundances obtained using these different methods are given in Table 5. A brief overview of these alternate methods is provided below.

The N2 method is mainly based on the N2/o2 line ratio. The ionization correction factors (ICF) of Izotov et al. (2006) were used to compute total abundances for N, Ne, and Ar. In case of S, we followed the correction given in Peimbert & Costero (1969). Subsequently, the log values of N/O, S/O, Ne/O, and Ar/O ratios were also computed. The resulted chemical abundances for the spatially resolved star-forming region in our sample of dwarf WR galaxies are presented in Table 4.

We have also derived the ionic abundances for other elements using the expression given by Izotov et al. (2006). Here, we again used the two-zone scheme for determining the ionic abundances. T_e[O III] is taken as the representative temperature for the high ionization potential ions such as Ne^+ and Ar^+, while T_e[O II] is taken as the representative temperature for the low ionization potential ions such as N^+ and S^+. The ionization correction factors (ICF) of Izotov et al. (2006) were used to compute total abundances for N, Ne, and Ar. In case of S, we followed the correction given in Peimbert & Costero (1969). Subsequently, the log values of N/O, S/O, Ne/O, and Ar/O ratios were also computed. The resulted chemical abundances for the spatially resolved star-forming region in our sample of dwarf WR galaxies are presented in Table 4.

Oxygen abundances corresponding to the H II regions are also determined using different methods such as N2, O3N2, and P-methods, which are empirically calibrated based on the photoionization models (Pilyugin 2001; Denicoló, Terlevich & Terlevich 2002; Pettini & Pagel 2004). These empirical methods allow to estimate oxygen abundances where the detection of [O III] λ4363 emission line is not made. The oxygen abundances obtained using these different methods are given in Table 5. A brief overview of these alternate methods is provided below.

The N2 method is mainly based on the N2/o2 line ratio. The ionization correction factors (ICF) of Izotov et al. (2006) were used to compute total abundances for N, Ne, and Ar. In case of S, we followed the correction given in Peimbert & Costero (1969). Subsequently, the log values of N/O, S/O, Ne/O, and Ar/O ratios were also computed. The resulted chemical abundances for the spatially resolved star-forming region in our sample of dwarf WR galaxies are presented in Table 4.
### Table 1: Line List and Observations

| Galaxy     | CGCG 041-023 (knot #a) | CGCG 041-023 (knot #b) | CGCG 041-023 (knot #c) | SBS 1222+614 (knot #a + b) | SBS 1222+614 (knot #c) |
|------------|------------------------|------------------------|------------------------|----------------------------|------------------------|
| O II       | 4101                   | 0.67 ± 0.04            | 2.2 ± 0.2              | 4.2 ± 0.04                 | 5.4 ± 0.04             |
| Ne III     | 3953                   | 0.63 ± 0.05            | 3.6 ± 0.2              | 0.70 ± 0.05                | 1.10 ± 0.05            |
| H β        | 4861                   | 2.89 ± 0.02            | 11.2 ± 0.1             | 2.10 ± 0.02                | 3.50 ± 0.02            |
| O III      | 4363                   | 0.14 ± 0.02            | -                      | 0.27 ± 0.03                | -                      |
| N II       | 6548                   | 0.014 ± 0.006          | -                      | -                          | -                      |
| H δ        | 6563                   | 7.83 ± 0.01            | 1.17 ± 0.03            | 30.2 ± 0.1                 | 4.24 ± 0.02            |
| N II       | 6583                   | 0.29 ± 0.01            | 0.08 ± 0.03            | 0.6 ± 0.1                  | 0.10 ± 0.01            |
| S II       | 6717                   | 0.34 ± 0.01            | 0.013 ± 0.001          | 1.1 ± 0.1                  | 0.20 ± 0.01            |
| S II       | 6731                   | 0.22 ± 0.01            | 0.008 ± 0.001          | 0.8 ± 0.1                  | 0.15 ± 0.01            |
| Ar III     | 7135                   | 0.18 ± 0.01            | -                      | 0.14 ± 0.01                | -                      |

### Figure 7: Comparison of Starburst Ages

Figure 7. A comparison of starburst ages estimated from the Hα and Hβ equivalent widths.

### Figure 8: WR Bump Detection

Figure 8. The blue WR bump detected in the spatially resolved star-forming regions of SBS 1222+614. The dashed-dot line represents the continuum fit. The solid line represents a Gaussian fit to the blue bump.
Using the above relation, the estimated oxygen abundances for the 
H II regions are given in the third column of Table 5.

Alloin et al. (1979) proposed a relation for estimating the oxygen
abundance in extragalactic H II regions, similar to the N2-method,
but using the \[O_3N_2 \equiv \log([O III] \lambda 5007/H\beta)/([N II] \lambda 6583/H\alpha)\]
index. This relation was revised by Pettini & Pagel (2004) using
137 extragalactic H II regions. They found that the relation is tight
at \[O_3N_2 \leq 1.9\]. The least square linear fit to the data in the range
\[-1 < O_3N_2 < 1.9\] yields the relation:

\[
12 + \log(O/H) = 8.73 - 0.320O_3N_2
\]  

(3)

In our sample of dwarf WR galaxies, all the H II regions satisfied
the condition \[O_3N_2 \leq 1.9\], which requires to use the above given
relation. The oxygen abundances estimated from the \[O_3N_2\]-method
are given in the fourth column of Table 5.

We also used P-method to estimate the oxygen abundance. This
method was proposed by Pilyugin (2000, 2001) and achieved a good
agreement to the results obtained with the direct \[Te\]-method. Pilyu-
gin found that the precision of oxygen abundance determination
with this method is \(~0.1\) dex. This method uses the index \[R_{23}\]
and excitation parameter \[P\], where these parameters are defined as

\[
R_{23} = \frac{[O II]\lambda 3727 + [O III]\lambda 4959 + [O III]\lambda 5007}{H\beta}
\]  

(4)

and

\[
P = \frac{[O III]\lambda 4959 + [O III]\lambda 5007}{[O II]\lambda 3727 + [O III]\lambda 4959 + [O III]\lambda 5007}
\]  

(5)

This method uses two-zone models for H II regions: a moderately
high-metallicity H II region with \[12 + \log(O/H) \geq 8.2\] and a low-
metallicity H II region. The best fit to the relations that can be
adopted for the oxygen abundance determination for the two-zone
models are given as

\[
12 + \log(O/H)_{\text{high}} = \frac{R_{23} + 54.2 + 59.45 P + 7.31 P^2}{6.07 + 6.71 P + 0.37 P^2 + 0.243 R_{23}}
\]  

(6)

and

\[
12 + \log(O/H)_{\text{low}} = 6.35 + 1.45 \log R_3 - 3.19 \log P
\]  

(7)

where the index \[R_3\] is defined as \([([O III] \lambda 4959 + [O III] \lambda 5007)/H\beta] \). The
oxygen abundance of all the spatially resolved H II regions in
our sample of dwarf WR galaxies was estimated by taking the mean
of the result from equations (6) and (7), because the H II regions in
our sample seem to belong to the intermediate metallicity region.
The estimated oxygen abundances using P-method are given in the
fifth column of Table 5. It may be noted here that all these empirical
relations to estimate oxygen abundance use emission line ratios
for lines at closeby wavelengths, hence these methods are not very
sensitive to errors in extinction corrections or flux calibration.

4 DISCUSSIONS

4.1 Comparison of metallicities from different indicators

The estimates of metallicity from different methods are given in
Table 5. The metallicities derived from strong emission-line meth-
ods may give significantly biased results if the region under study
have different structural properties (e.g. hardness of the ionizing
radiation field and morphology of the nebulae) than those estimated
using the empirically calibrated methods (Stasińska 2010). There-
fore, in order to test reliability of the empirical calibration relations,
we made comparisons of the \[Te\]-based metallicity with the metal-
llicity derived using N2-, O3N2-, and P-method. In our comparison
Table 4. The physical conditions and chemical abundances of star-forming regions in galaxies.

| Parameters | IC 3521 (knot #a) | IC 3521 (knot #b) | CGCG 038-051 (knot #a) | CGCG 038-051 (knot #b) | CGCG 041-023 (knot #a) | CGCG 041-023 (knot #b) | CGCG 041-023 (knot #c) | SBS 1222+614 | SBS 1222+614 |
|------------|-------------------|-------------------|------------------------|------------------------|------------------------|------------------------|------------------------|--------------|--------------|
| $T_e$ [O III] (K) | 10000$^b$ | 10000$^b$ | 16545 ± 2236 | 16155 ± 343 | 10000$^b$ | 12346 ± 935 | 10000$^b$ | 10000$^b$ | 13822 ± 292 | 14403 ± 239 |
| $T_e$ [O II] (K) | 10000$^b$ | 10000$^b$ | 14581 ± 1565 | 14308 ± 240 | 10000$^b$ | 11642 ± 814 | 10000$^b$ | 10000$^b$ | 12675 ± 204 | 13082 ± 167 |
| $n_e$ (cm$^{-3}$) | 100$^d$ | 100$^d$ | <100 | 603 ± 36 | <100 | <100 | 100$^d$ | 100$^d$ | <100 | <100 |
| 12+log(O$^+$/H$^+$) | – | – | 7.57 ± 0.11 | 7.63 ± 0.02 | 8.01 ± 0.05 | 7.91 ± 0.08 | – | – | 7.95 ± 0.02 | 7.86 ± 0.02 |
| 12+log(O$^+$/H$^+$) | – | – | 7.08 ± 0.13 | 7.10 ± 0.05 | – | 7.54 ± 0.10 | – | – | 7.42 ± 0.03 | 7.34 ± 0.02 |
| 12+log(O/H) | 8.61 ± 0.01$^a$ | 8.59 ± 0.01$^a$ | 7.69 ± 0.09 | 7.74 ± 0.02 | 8.01 ± 0.05 | 8.07 ± 0.06 | 8.23 ± 0.10$^a$ | 8.20 ± 0.03$^a$ | 8.06 ± 0.02 | 7.98 ± 0.01 |
| 12+log(N$^+$/H$^+$) | – | 7.18 ± 0.01 | 5.59 ± 0.08 | 5.67 ± 0.04 | – | 6.01 ± 0.06 | – | – | 5.64 ± 0.03 | 5.55 ± 0.04 |
| 12+log(N/H) | – | 7.66 ± 0.01 | 6.19 ± 0.16 | 6.30 ± 0.06 | – | 6.53 ± 0.12 | – | – | 6.27 ± 0.04 | 6.18 ± 0.05 |
| 12+log(N/O) | – | 3$^d$ | 4.00 ± 1.29 | 4.28 ± 0.45 | – | 3.30 ± 0.79 | – | – | 4.27 ± 0.29 | 4.18 ± 0.27 |
| log(N/H) | – | −0.93 ± 0.01 | −1.50 ± 0.18 | −1.44 ± 0.06 | – | −1.53 ± 0.14 | – | – | −1.79 ± 0.05 | −1.80 ± 0.05 |
| log(N/E) | – | – | 6.83 ± 0.17 | 6.88 ± 0.07 | – | 7.34 ± 0.10 | – | – | 7.52 ± 0.03 | 7.50 ± 0.04 |
| 12+log(He$^+$/H$^+$) | – | – | 6.88 ± 0.17 | 6.92 ± 0.08 | – | 7.39 ± 0.11 | – | – | 7.56 ± 0.03 | 7.54 ± 0.04 |
| 12+log(He/H) | – | – | 1.10 ± 0.10 | 1.10 ± 0.02 | – | 1.13 ± 0.07 | – | – | 1.10 ± 0.02 | 1.10 ± 0.01 |
| log(He/O) | – | – | −0.81 ± 0.19 | −0.82 ± 0.08 | – | −0.67 ± 0.12 | – | −0.50 ± 0.04 | −0.43 ± 0.04 |
| 12+log(S$^+$/H$^+$) | – | 6.16 ± 0.02 | 5.27 ± 0.07 | 5.50 ± 0.02 | 5.63 ± 0.09 | 5.48 ± 0.06 | – | – | 5.35 ± 0.02 | 5.32 ± 0.02 |
| 12+log(S/H) | – | 6.64 ± 0.02 | 5.88 ± 0.18 | 6.14 ± 0.06 | 6.23 ± 0.09 | 6.01 ± 0.13 | – | – | 5.99 ± 0.04 | 5.95 ± 0.04 |
| log(S/O) | – | 3$^d$ | 4.09 ± 1.51 | 4.40 ± 0.53 | 4$^d$ | 3.33 ± 0.92 | 4.39 ± 0.34 | 4.29 ± 0.31 |
| log(O/H) | – | −1.95 ± 0.02 | −1.80 ± 0.20 | −1.60 ± 0.06 | −1.78 ± 0.10 | −2.06 ± 0.15 | −2.06 ± 0.04 | −2.03 ± 0.04 |
| 12+log(Ne$^+$/H$^+$) | – | – | 5.26 ± 0.08 | 5.33 ± 0.05 | 5.57 ± 0.15 | 5.57 ± 0.06 | – | – | 5.52 ± 0.04 | 5.46 ± 0.03 |
| 12+log(Ne/H) | – | – | 5.25 ± 0.09 | 5.32 ± 0.05 | 5.57 ± 0.15 | 5.53 ± 0.06 | – | – | 5.52 ± 0.04 | 5.45 ± 0.03 |
| log(N/E) | – | – | 0.97 ± 0.08 | 0.99 ± 0.03 | 1$^d$ | 0.92 ± 0.05 | – | – | 0.99 ± 0.02 | 0.99 ± 0.02 |
| log(Ar/O) | – | – | −2.44 ± 0.12 | −2.42 ± 0.05 | −2.44 ± 0.16 | −2.54 ± 0.09 | – | – | −2.54 ± 0.04 | −2.52 ± 0.04 |

Notes: $^a$The values of 12 + log(O/H) that are estimated using N2-method, as oxygen lines are not detected in the spectrum.
$^b$The values of electron temperatures that could not be estimated due to the absence of oxygen [O III]λ4363 line are assumed to be 10 000 K.
$^c$The values of electron densities that could not be estimated due to the absence of doublet sulfur [S II]λλ6717, 6731 lines are assumed to be 100 cm$^{-3}$.
$^d$The values of ICFs that could not be estimated due to the absence of oxygen [O II]λλ3726 line are assumed to be either equal to an approximate value found in other regions within the same galaxy or an average value found in the literature if it is not available for any region of the galaxy.
as shown in Fig. 11, all the empirical methods i.e. N$_2$-, O$_3$N$_2$-, and P-method are found to yield metallicity very close to that estimated from the direct T$_e$-method. The best agreement is found between T$_e$- and N$_2$-methods, which shows a difference in the metallicities less than 0.06 dex on average. In the literature, it is however noticed that the P-method shows the best agreement with T$_e$-method for high metallicity galaxies (e.g. Shi et al. 2005; López-Sánchez & Esteban 2010b), and such high metallicity galaxies are absent in our analysis. It can be seen that the two H II regions that have low-metallicity (12 + log(O/H) < 7.8) show large differences up to ~0.4 and ~0.3 dex, respectively, in all the cases. The large difference for the two regions with low metallicity is not surprising as it is known that the empirical methods overestimate the oxygen abundance in comparison to that from the T$_e$-method in low-metallicity regions (Pilyugin 2000, 2001). Such large differences in low-metallicity regions were also noticed by López-Sánchez & Esteban (2010b). Overall, it can be stated that although there is a large scatter, the empirical methods provide estimates of metallicities in good agreement with those derived from the direct T$_e$-method. The difference between empirical and T$_e$-based estimates is between 0.02 and 0.4 dex. This estimated difference is in good agreement with those derived in other similar studies available in the literature (e.g. Shi et al. 2005; Kewley & Ellison 2008; López-Sánchez & Esteban 2010b). Overall, the presented analysis in this work is consistent with similar previous studies available in the literature (Shi et al. 2005; García-Rojas & Esteban 2007; Esteban et al. 2009; López-Sánchez & Esteban 2010b).

A detailed discussion on reasons responsible for differences in the metallicity estimates from different methods can be found in Kennicutt et al. (2003) and López-Sánchez & Esteban (2010b). The observed differences between various estimates of metallicities are also discussed in Stasińska (2002) and Shi et al. (2005). The observed discrepancies in the estimates of oxygen abundance from different methods are explained in terms of two main sources: (i) a lack of sufficient number of H II regions with an accurate T$_e$-based estimates of oxygen abundance used in calibrations of the empirical methods and (ii) a systematic offset between the observed forbidden-line temperatures and the nebular electron temperature used for calibrating photoionization models (Kennicutt et al. 2003). The latter effect is more important due to the fact that the temperature fluctuations and gradients are known to exist in the ionized gas of star-bursting galaxies (Peimbert 1967; Stasińska 2002, 2005; Peimbert et al. 2007). Moreover, Guseva, Izotov & Thuan (2006) and Guseva et al. (2007) in their work aimed at determining the Balmer jump temperature in a large sample of low-metallicity H II regions quantified the temperature fluctuation parameter to be $T_e^2 \lesssim 0.02$ in the high temperature ($T_e > 1.1 \times 10^4$ K) star-bursting regions. The differences can also be due to several other factors such as galaxies with different ionization parameters, different chemical evolution, and star formation histories. Therefore, a proper choice of empirical methods for estimating metallicity plays an important role and must be used with caution.

### Table 5. The values of 12+log(O/H) determined from different indicators.

| Galaxy     | knot | N$_2$-Method 12+log(O/H) | O$_3$N$_2$-Method 12+log(O/H) | P-Method 12+log(O/H) | T$_e$-Method 12+log(O/H) | Median 12+log(O/H) | Weighted mean 12+log(O/H) |
|------------|------|--------------------------|-------------------------------|---------------------|-------------------------|---------------------|-------------------------|
| IC 3521    | #a   | 8.61 ± 0.01              | –                             | –                   | 8.61 ± 0.01             | 8.61 ± 0.01         | 8.61 ± 0.01              |
| IC 3521    | #b   | 8.59 ± 0.01              | –                             | –                   | 8.59 ± 0.01             | 8.59 ± 0.01         | 8.59 ± 0.01              |
| CGCG 038-051 #a | 7.97 ± 0.02 | 8.00 ± 0.01 | 8.11 ± 0.07 | 7.69 ± 0.09 | 7.99 ± 0.01 | 7.99 ± 0.01 | 7.99 ± 0.01 |
| CGCG 038-051 #b | 7.99 ± 0.02 | 8.01 ± 0.01 | 8.10 ± 0.09 | 7.74 ± 0.02 | 8.00 ± 0.01 | 7.96 ± 0.01 | 7.96 ± 0.01 |
| CGCG 038-051 #c | –   | –                       | –                             | –                   | –                       | –                   | –                       |
| CGCG 041-023 #a | 8.08 ± 0.01 | 8.07 ± 0.01 | 8.11 ± 0.03 | 8.07 ± 0.06 | 8.08 ± 0.01 | 8.08 ± 0.01 | 8.08 ± 0.01 |
| CGCG 041-023 #b | 8.23 ± 0.10 | –                   | –                             | –                   | –                       | 8.23 ± 0.10         | 8.23 ± 0.10              |
| CGCG 041-023 #c | 8.20 ± 0.03 | –                   | –                             | –                   | –                       | 8.20 ± 0.03         | 8.20 ± 0.03              |
| SBS 1222+614 #a+b | 7.93 ± 0.02 | 7.93 ± 0.01 | 8.10 ± 0.03 | 8.06 ± 0.02 | 8.00 ± 0.02 | 7.96 ± 0.01 | 7.96 ± 0.01 |
| SBS 1222+614 #c | 7.98 ± 0.02 | 7.96 ± 0.01 | 8.12 ± 0.08 | 7.98 ± 0.01 | 7.98 ± 0.02 | 7.97 ± 0.01 | 7.97 ± 0.01 |

### 4.2 Spatial variations in chemical compositions

The estimates of various chemical abundances such as O, N, Ne, and Ar from the direct T$_e$-method and oxygen abundance from different indicators for the spatially resolved star-forming region in the galaxies are given in Tables 4 and 5, respectively. In these tables, it can be noticed that the chemical abundances across the galaxies are, in general, homogeneous within the uncertainties in the estimates, except that in case of knot #c in the galaxy CGCG 038-051 where the metallicity is found to be considerably different (~0.3 dex) from that found for other knots in the same galaxy. We show here that such differences can be due to uncertainty in the electron temperature that in these cases was assumed as $10^4$ K in the absence of direct T$_e$ estimate due to non-detection of temperature sensitive oxygen line of [O III] $\lambda$4363. Based on an investigation of chemical history of dwarf galaxies studied in the literature which show homogeneous chemical abundances, we found that such galaxies usually show a nearly constant electron temperature in all distinct H II regions within the same galaxies (Kobulnicky et al. 1997; Lagos et al. 2009). The constant electron temperature is also seen in the cases of different knots in SBS 1222+614 and CGCG 038-051 in this work with measured T$_e$. In CGCG 038-051, temperature for the knot #c was assumed as $10^4$ K in Table 4, while temperature for other knots has T$_e$ close to ~16 500 K. We therefore re-estimated the oxygen abundance for the knot #c in CGCG 038-051 by assuming the same electron temperature as those estimated for other knots in the galaxies (see Table 4). The revised value for metallicity for the knot #c is found as 7.40 ± 0.12 in CGCG 038-051. This value is nearly close to those estimated for other knots in the same galaxy within the measurement uncertainties. Our analysis implies that an uncertainty in electron temperature can lead to a considerable difference in the metallicity estimates for distinct H II regions. This also implies that uncertainty in the estimates of electron temperature plays a major role in the estimates of oxygen abundance. Izotov et al. (2006) observed several H II complexes in SBS 0335-052E and found a decreasing trend of oxygen abundance between 0.10 and 0.14 dex as they proceeded from one end to other end of the galaxy. This trend was interpreted as self-enrichment by heavy elements. However, they also suggested that the error in the estimates of T$_e$ can lead to an apparent variation in the oxygen abundance in SBS 0335-052E. Overall, we conclude that all four galaxies in...
our sample are chemically homogeneous, similar to other galaxies studied in the literature (e.g. Skillman, Kennicutt & Hodge 1989; Kobulnicky & Skillman 1996, 1998; Lee et al. 2006; Croxall et al. 2009; Berg et al. 2012).

The separations between the H II regions in these galaxies are in the range of 0.3–2.4 kpc. This implies that a homogeneity in the chemical abundances in the studied galaxies is observed over large spatial scales. Such a chemical homogeneity in galaxies can be expected if the processed metals injected into the ISM from past bursts of star formation have cooled down, well mixed, and homogeneously distributed across the whole extent of the galaxy. While the newly synthesized metals formed in the current episode of star formation are still in hot gas-phase \( (T \sim 10^7 \text{ K}) \) (Kobulnicky & Skillman 1996; Papaderos et al. 2006; Cárs et al. 2009; Lagos et al. 2009; Hägele et al. 2011; Pérez-Montero et al. 2011; García-Benito & Pérez-Montero 2012; Lagos & Papaderos 2013), not observable at optical bands. Therefore, the currently observed metals in the optical band are from previous episodes of star formation. A possible mechanism responsible for the metal dispersal and mixing at large spatial scales can be bar-induced rotation or shear, in particular, in massive galaxies (e.g. Roy & Kunth 1995). Alternatively, the global hydrodynamical process such as starburst-driven super-shells and/or gas inflows can be another possible mechanism for transporting and mixing the metals over the whole extent of the galaxy in typical time-scales of few \( 10^4 \text{ yr} \) (Tenorio-Tagle 1996).

A metal enrichment to the ISM local to the star-bursting region can take place due to winds from the most massive stars and the supernova explosions near the youngest star-bursting region. For example, Kobulnicky & Skillman (1996) reported an oxygen over-abundance by \( \sim 0.1 \text{ dex} \) at the locations of the young starburst in NCG 4214 (dwarf irregular WR galaxy), possibly from recent supernova events. At least one of star-forming regions \( (\lesssim 6 \text{ Myr in age}) \) in each galaxy studied in this work are observed in WR phase, which appears before supernova explosions of massive stars (Meynet & Maeder 2005). Therefore, there is a possibility that the ejection of newly synthesized heavy metals in such star-forming regions in WR phase have not yet taken place through supernova explosions. In fact, Jaiswal & Omar (2016) have predicted based on radio continuum data analysis that these galaxies have radio deficiency, most likely due to a lack of recent supernova events. However, nitrogen-enrichment as expected in these star-forming regions is not detected. The metal enrichment of local ISM through ejection in the luminosity-driven stellar winds from massive WR and/or other O or OB-type stars will be too small to be detected in this work. Based on these analysis, we have concluded that the observed chemical homogeneity in our sample of dwarf WR galaxies hosting very young massive star formation \( (\lesssim 10 \text{ Myr}) \) is most likely a consequence of the presence of cooled and well-mixed metals formed in the previous episodes of star formation \( (> 100 \text{ Myr}) \) and the metals formed in the current episode of star formation are still likely to be in hot gas-phase and not seen in optical bands.

### 4.3 \( \alpha \)-Elements to oxygen ratios

Fig. 12 shows the values of \( \log(\text{Ne/O}), \log(\text{S/O}), \) and \( \log(\text{Ar/O}) \) as a function of \( 12 + \log(O/H) \) for all the spatially resolved H II regions analyzed in this work. We find that the abundance ratios of S, Ne, and Ar relative to oxygen are nearly constant, independent of metallicity. These trends are consistent with those seen in other dwarf galaxies previously studied in the literature (Izotov & Thuan 1999; Izotov et al. 2006; López-Sánchez & Esteban 2010b). From this work, the mean values of \( \log(\text{Ne/O}), \log(\text{S/O}), \) and \( \log(\text{Ar/O}) \) ratios are estimated at \(-0.65 \pm 0.05, -1.86 \pm 0.04, \) and \(-2.48 \pm 0.04, \) respectively. These values are comparable within errors with the previously reported values for star-bursting dwarf galaxies (e.g. Izotov & Thuan 1999; Izotov et al. 2006; López-Sánchez & Esteban 2010b). From this work, the mean values of \( \log(\text{Ne/O}), \log(\text{S/O}), \) and \( \log(\text{Ar/O}) \) ratios are estimated at \(-0.65 \pm 0.05, -1.86 \pm 0.04, \) and \(-2.48 \pm 0.04, \) respectively. These values are comparable within errors with the previously reported values for star-bursting dwarf galaxies (e.g. Izotov & Thuan 1999; Izotov et al. 2006). Izotov & Thuan (1999) estimated the mean values of \( \log(\text{Ne/O}), \log(\text{S/O}), \) and \( \log(\text{Ar/O}) \) ratios as \(-0.72 \pm 0.06, -1.56 \pm 0.06, \) and \(-2.26 \pm 0.09, \) respectively. Moreover, López-Sánchez & Esteban (2010b) found the mean values as \( 0.70 \pm 0.13, -1.68 \pm 0.10, \) and \(-2.37 \pm 0.12, \) for the \( \log(\text{Ne/O}), \log(\text{S/O}), \) and \( \log(\text{Ar/O}) \) ratios, respectively, in a similar sample of dwarf WR galaxies as studied in this work.
Figure 12. The values of log(Ne/O), log(S/O), and log(Ar/O) plotted against 12 + log(O/H), as determined in this work for our sample of dwarf WR galaxies.

Despite uncertainties in the estimated values of α-elements to oxygen ratios, we noticed that the Ne/O and S/O ratios show slightly increasing and decreasing trends with increasing metallicity, respectively. This trend has also been reported in the literature. For example, Izotov et al. (2006) reported an increasing trend of Ne/O ratio with increasing oxygen abundance, most likely due to a moderate depletion of oxygen into dust grains in metal-rich galaxies. Similarly, Verma et al. (2003) reported a slight decreasing trend in S/O ratio in relatively high-metallicity star-burst galaxies due to depletion of sulfur onto dust grains.

In a scenario of chemical evolution in galaxies, it is believed that the N/O ratio is a powerful indicator of galaxy evolution (Pilyugin, Vílchez & Contini 2004; Mollá et al. 2006). The origin of nitrogen in galaxies is an ongoing debate since several decades. In Fig. 13, we investigated the relation between log(N/O) ratio and oxygen abundance [12 + log(O/H)] for a large sample of dwarf WR galaxies with our data also included in it. In this figure, it can be seen that the values of log(N/O) show a varying trend depending on two metallicity regimes: low metallicity (12 + log(O/H) ≲ 8) and high metallicity (12 + log(O/H) ≳ 8). The low-metallicity H II regions have a nearly constant value of log(N/O) ratio independent of 12 + log(O/H), while an increasing trend for log(N/O) ratio with increasing oxygen abundance is observed in the high-metallicity H II regions. This trend is well known and has been reported in various studies. However, it is still not completely understood and is presently explained in the literature as follows: the observed behavior of log(N/O) with 12 + log(O/H) is generally explained in terms of two sources of enrichment termed as primary and secondary. Massive stars produce small amounts of nitrogen in early phase of evolution, which is termed as the primary production of nitrogen (Edmunds & Pagel 1978; Alloin et al. 1979; Izotov & Thuan 1999). The low and intermediate mass stars produce nitrogen and other elements heavily enriching ISM with a time lag as compared to the primary production. The latter delayed process is often termed as the secondary production (Henry et al. 2000). The low metallicity region (12 + log(O/H) ≲ 8) with a constant N/O ratio is believed to be from the primary production of nitrogen in massive stars (e.g. Garnett 1990; Vila Costas & Edmunds 1993; Thuan, Izotov & Lipovetsky 1995; van Zee et al. 1998). At high metallicity, a steep increase in N/O ratio is believed to be due to increased secondary production and partly also due to selective depletion of oxygen in dust grains (e.g. Kobulnicky & Skillman 1998; Izotov & Thuan 1999; Pilyugin, Thuan & Vílchez 2003; Izotov et al. 2006; Mollá et al. 2006).

Some WR galaxies also show excess nitrogen in the range of 0.25–0.85 dex in the relation between log(N/O) and 12 + log(O/H) over all the metallicity regimes (Kobulnicky et al. 1997; Pustilnik et al. 2004; López-Sánchez et al. 2007; Brinchmann et al. 2008; López-Sánchez & Esteban 2010b; Jaiswal & Omar 2013; Karthick et al. 2014). The excess of nitrogen in WR galaxies is attributed to nitrogen ejection in luminosity-driven stellar winds of WR stars. However, we did not detect excess nitrogen in these star-bursting regions with WR features in our galaxy sample (see Fig. 13). The N/O ratio is found to be consistent with the normal trend known for non-WR star-bursting galaxies. Presently, this behaviour is not completely understood. Consistent with our previous conclusion as made in Section 4.2, it is possible that the ejected extra nitrogen from WR stars is not yet sufficiently cooled down to be detected at optical wavebands. It is worth to point out that absence of extra nitrogen has also been reported in several other WR galaxies (e.g. Kobulnicky & Skillman 1996; Monreal-Ibero, Walsh & Vílchez 2012; Westmoquette et al. 2012; James et al. 2013).

4.4 Luminosity–metallicity relation

The luminosity–metallicity relation for galaxies has been used as a tool for tracing evolution of galaxies as more luminous galaxies are supposed to contain a large fraction of processed material (McGaugh & de Blok 1997; Bell & de Jong 2000; Boselli et al. 2001). This relation is known since the early works of Lequeux et al. (1979) and Rubin, Ford & Whitmore (1984). Thereafter, the relation was confirmed in many similar studies in the literature (e.g. 2019).
Figure 13. log(N/O) versus 12 + log(O/H), as determined from this study for our sample of dwarf WR galaxies and for other galaxies from the literature.

Figure 14. The luminosity–metallicity relation for the galaxies studied in this work and in the literature. The metallicity is expressed in units of 12 + log(O/H) and the luminosity is expressed in terms of absolute magnitude in B band.

Bothun et al. 1984; Wyse & Silk 1985; Skillman et al. 1989; Vilas-Costas & Edmunds 1992; Zaritsky et al. 1994; Richer & McCall 1995; Duc & Mirabel 1998; Garnett 2002; Tremonti et al. 2004; Shi et al. 2005; van Zee & Haynes 2006; López-Sánchez & Esteban 2010b). We plotted the B-band luminosity–metallicity relation for galaxies in our sample in Fig. 14. In this figure, we have included other similar dwarf WR galaxies from the sample of López-Sánchez & Esteban (2010b) and their best linear-fit relations. This figure also includes some other similar relations reported in the literature, e.g. the known luminosity–metallicity relation for dwarf and irregular galaxies in Richer & McCall (1995), van Zee & Haynes (2006), Tremonti et al. (2004) and Skillman et al. (1989). Here, our galaxies appear to follow normal luminosity–metallicity relation. The luminosity–metallicity relation has also been used to identify tidal dwarf galaxies by locating high metallicity galaxies for their given optical luminosity (Duc & Mirabel 1998; López-Sánchez & Esteban 2010b). Our analysis indicates that the dwarf WR galaxies studied in this work trace a normal evolution as seen for other normal dwarf galaxies and these are not tidal dwarf galaxies.

4.5 Local galaxy environment

In this section, we discuss the local environment of each individual galaxy in our sample. The galaxy density within a comoving volume
of 0.5 Mpc in projected radius and ± 250 km s$^{-1}$ in radial velocity range from the recession velocity of the target galaxies is presented. The galaxy density is estimated using the NED tool (https://ned.ipac.caltech.edu/forms/denenv.html). The local galaxy environment of each individual galaxies is discussed below.

4.5.1 IC 3521

IC 3521 belongs to the Virgo Cluster of galaxies. A total of 41 galaxies are listed in the NED in the defined space volume, implying an average galaxy density of ~80 Mpc$^{-3}$. All the neighbour galaxies have velocities in the range of 439–833 km s$^{-1}$. This indicates the presence of a galaxy-rich dense environment around IC 3521. Among these neighbour galaxies, a total of nine and three galaxies in the vicinity of IC 3521 are dE and dIrr types, respectively, and only nine galaxies are big spiral or lenticular types. A total of 21 galaxies are still morphologically unclassified.

4.5.2 CGCG 038-051

In the defined volume, a total of nine galaxies is listed. It represents an average galaxy density of ~19 Mpc$^{-3}$. The neighbouring galaxies are found to be in a narrow velocity range of 986–1070 km s$^{-1}$. Except two dwarf galaxies (LSBC L1-137 and LSBC L1-137A), all other galaxies are giant systems that have well-developed bright spiral arms and disc. These galaxies together appear to be residing in a group-like environment.

4.5.3 CGCG 041-023

CGCG 041-023 belongs to the VV 462 galaxy group. In the vicinity of CGCG 041-023, a total of three galaxies are listed in the NED, which in turn gives an estimate of galaxy density as ~8 Mpc$^{-3}$ within the defined volume. Two neighbouring galaxies have velocity in a very narrow range of 1350–1359 km s$^{-1}$, while one has velocity about ~1482 km s$^{-1}$. Interestingly, all these neighbouring galaxies are dwarf systems, and their SDSS colour composite images show the presence of blue regions extended over the galaxies extent representing an ongoing star formation activities in them. It seems that CGCG 041-023, together with neighbouring galaxies, forms a small group of star-forming dwarf galaxies.

4.5.4 SBS 1222+614

Within the defined volume, a total of four galaxies are listed, implying an average galaxy density of ~10 Mpc$^{-3}$. All these neighbouring galaxies have velocities in a very narrow range of 709–722 km s$^{-1}$, except for SDSS J1219.5+11.63110.0, which has a velocity of 516 km s$^{-1}$. Interestingly, all the neighbouring galaxies are dwarf galaxies that are blue in optical band as seen in their SDSS colour composite images. The galaxies MCG +10-18-044 and UGC 7534 are closely associated with SBS 1222+614 and UGC 7544 as revealed in the work of Jaiswal & Omar (private communication) and Stil & Israel (2002a,b). SBS 1222+614, together with its neighbouring galaxies, indicates a small group of galaxies.

5 SUMMARY AND CONCLUSIONS

The spatially resolved optical spectroscopic observations of four nearby dwarf Wolf-Rayet (WR) galaxies were presented here. These galaxies are residing in group and cluster environments with widely varying galaxy density in the range of 8–80 Mpc$^{-3}$. This environment is suitable for galaxy–galaxy interactions, which might have triggered star formation in these galaxies. The ages of the most recent starburst events in the galaxies are found between 3 and 10 Myr. The gas-phase metallicity [12 + log(O/H)] for all the spatially resolved star-forming regions is derived using several indicators and compared with each other. This comparison indicated that although there is a large scatter in the estimates of metallicities from different indicators, the empirical methods provide the estimates of metallicities that are in good agreement with those derived from the direct T_e-method. Consistent with other similar studies available in the literature, the differences between empirical and T_e-based estimates of oxygen abundances are found between 0.02 and 0.4 dex. This study also shows that different star-forming regions within the galaxies are chemically homogeneous. Against an expectation of N-enrichment in WR galaxies, these galaxies show a normal N/O ratio for their given metallicities. It is speculated here that the newly synthesized metals from the current episode of star formation in these WR galaxies are possibly in hot gas-phase, and the metals from the previous episodes have cooled down and well mixed across the whole extent of galaxies, which makes galaxies chemically homogeneous with normal N/O ratio. The luminosity–metallicity relations for these galaxies are consistent with the previously known relation for normal dwarf and large spiral galaxies, indicating that these dwarf WR galaxies are evolving in normal way and do not belong to a category of tidal dwarf galaxies.

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REFERENCES

Allen D. A., Wright A. E., Goss W. M., 1976, MNRAS, 177, 91
Alloin D., Collin-Souffrin S., Joly M., Vigroux L., 1979, A&A, 78, 200
Aloisi A., van der Marel R. P., Mack J., Leitherer C., Sirianni M., Tosi M., 2005, ApJ, 631, L45
Amorín R., Aguerri J. A. L., Muñoz-Tuñón C., Cairós L. M., 2009, A&A, 501, 75
Amorisco N. C., Evans N. W., van de Ven G., 2014, Nature, 507, 335
Baldwin J. A., Phillips M. M., Terlevich R., 1981, PASP, 93, 5
Belfiore F., Maiolino R., Bundy K., Thomas D., Maraston C., Wilkinson D., Sánchez S. F., Bershady M., 2015, MNRAS, 449, 867
Bell E. F., de Jong R. S., 2000, MNRAS, 312, 497
Bergvall N., Östlin G., 2002, A&A, 390, 891
Berg D. A. et al., 2012, ApJ, 754, 98
Bosselli A., Gavazzi G., Donas J., Scodellaro G., 2001, ApJ, 121, 753
Bothun G. D., Romanishin W., Strom S. E., Strom K. M., 1984, AJ, 89, 1300
Brinchmann J., Kunth D., Durret F., 2008, A&A, 485, 657
Cairós L. M., Caon N., Vilchez J. M., González-Pérez J. N., Muñoz-Tuñón C., 2001, ApJS, 136, 393
Cairós L. M., Caon N., Papaderos P., Gehrz R., Siebert A., 2006, ApJ, 707, 1676
