The ionized gas at the centre of IC 10: a possible localized chemical pollution by Wolf–Rayet stars

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ABSTRACT
We present results from integral field spectroscopy with the Potsdam Multi-Aperture Spectrograph at the 3.5-m telescope at Calar Alto Observatory of the intense star-forming region [HL90] 111 at the centre of the starburst galaxy IC 10. We have obtained maps with a spatial sampling of 1 × 1 arcsec2 = 3.9 × 3.9 pc2 of different emission lines and analysed the extinction, physical conditions, nature of the ionization and chemical abundances of the ionized gas, as well determined locally the age of the most recent star formation event. By defining several apertures, we study the main integrated properties of some regions within [HL90] 111. Two contiguous spaxels show an unambiguous detection of the broad He II λ4686 emission line, this feature seems to be produced by a single late-type WN star. We also report a probable N and He enrichment in the precise spaxels where the Wolf–Rayet (WR) features are detected. The enrichment pattern is roughly consistent with that expected for the pollution of the ejecta of a single or a very small number of WR stars. Furthermore, this chemical pollution is very localized (∼2 arcsec ∼7.8 pc) and it should be difficult to detect in star-forming galaxies beyond the Local Volume. We also discuss the use of the most common empirical calibrations to estimate the oxygen abundances of the ionized gas in nearby galaxies from 2D spectroscopic data. The ionization degree of the gas plays an important role when applying these empirical methods, as they tend to give lower oxygen abundances with increasing ionization degree.

Key words: Stars: Wolf–Rayet – galaxies: abundances – galaxies: dwarf – galaxies: individual: IC 10 – galaxies: ISM – galaxies: starburst.

1 INTRODUCTION
Dwarf and irregular galaxies are ideal laboratories to study the interaction between massive stars and the interstellar medium (ISM). Indeed, massive stars do not only provide the energetic radiation that ionizes the H I clouds into H II regions, but they also inject mechanical energy into the surrounding medium, both via strong stellar winds and supernova (SN) explosions, which create shells and bubbles and may induce the birth of new stars. The effects of the massive stars in the ISM are especially strong when they are gathered together in large clusters; their actions can even affect the nearby intergalactic medium (IGM). Strong star-forming regions, which may be found in galaxies covering a wide range of masses, may enrich both the ISM and the IGM. Actually, it is still unclear whether the chemical enrichment provided by massive stars is an instantaneous event or if the new synthesized heavy elements must cool before becoming part of the ISM (e.g. Tenorio-Tagle 1996; Kobulnicky & Skillman 1996, 1997, 1998; Kobulnicky et al. 1997; Henry, Edmunds & Köppen 2000; van Zee & Haynes 2006; López-Sánchez & Esteban 2010b). All these processes have a large effect on the formation and evolution of galaxies.

Nearby dwarf galaxies have the advantage that they can be observed at high spatial resolution and even, in some cases, their stars are resolved. This allows a detailed analysis of the interplay between the neutral and ionized components of the ISM and the massive stars (e.g. Thron & Willcocks 2005; van Eymeren et al. 2007, 2009a,b, 2010; Monreal-Ibero et al. 2010) and constrains the kinematical and chemical evolution of the galaxies. Recently, our group confirmed a localized chemical enrichment in the nearby (4 Mpc) blue compact dwarf galaxy (BCDG) NGC 5253 (López-Sánchez et al. 2007). The nitrogen pollution (and probably also helium) found in a particular area of the galaxy seems to be a consequence of the ejecta of Wolf–Rayet (WR) stars. Evidences of possible nitrogen pollution have been
only reported in some few starbursts, but the majority of them also showing WR features (Kobulnicky et al. 1997; Pastilnik et al. 2004; James et al. 2009; López-Sánchez & Esteban 2010a,b). However, NGC 5253 remains as the only known star-forming galaxy where a localized chemical enrichment has been definitively established (Walsh & Roy 1989; Kobulnicky et al. 1997; López-Sánchez et al. 2007; Monreal-Ibero et al. 2010).

The advent of the 2D spectroscopy allows to explore this issue more efficiently, as this technique permits to record simultaneously the optical/near-infrared (NIR) spectra of regions within the galaxies without the limitations of long-slit observations. In particular, spectroscopy of dwarf, star-forming galaxies using integral field units (IFUs) provides a very powerful tool to constrain the physical, chemical and kinematical properties of the ionized gas within these objects (e.g. García-Lorenzo et al. 2008; Lagos et al. 2009; Cairós et al. 2009a,b, 2010; James et al. 2009; James, Tsamis & Barlow 2010), to look for the places where massive stars are located, to study the underlying stellar population and its kinematics via the analysis of the continuum and the absorption lines, and finally to combine all the results to understand the feedback between massive stars and the ISM (e.g. Thurow & Wilcots 2005; Kehrig et al. 2008; Alonso-Herrero et al. 2009; Bordalo, Plana & Telles 2009; Monreal-Ibero et al. 2010). Here, we present an optical 2D spectroscopical analysis of a particularly interesting and intense star-forming region within the nearest starburst, the galaxy IC 10. Although our main aim is to look for a localized chemical enrichment within the H\textsc{ii} region as a consequence of the massive stars, we will also analyse the extinction, ionization structure, chemical abundances and age of the most recent star formation burst in this particular area of IC 10.

Sometimes defined as an irregular galaxy, IC 10 (Fig. 1) actually is the only known starburst within the Local Group. Because of its low mass (Mateo 1998), high star formation activity (i.e. Hodge & Lee 1990; Leroy et al. 2006), low metallicity – 12+log(O/H) = 8.26; (Skillman, Kennicutt & Hodge 1989; Garnett 1990; Magrini & Gonçalves 2009) – its very extended, clumpy and peculiar distribution of neutral gas (Shostak & Skillman 1989; Wilcots & Miller 1998; Juette et al., in preparation), high far-infrared emission (Melisse & Israel 1994), non-thermal radio-continuum emission (Yang & Skillman 1993) and the relative importance of its young stellar population (i.e. Sakai, Madore & Freedman 1999; Borissova et al. 2000; Hunter 2001; Vacca, Sheehy & Graham 2007) which includes a large number of WR stars (Massey, Armandroff & Conti 1992; Massey & Johnson 1998; Massey & Holmes 2002), IC 10 is usually classified as a BCDG (Richer et al. 2001). The high carbon-rich WR stars to nitrogen-rich WR stars ratio in IC 10 (the WC/WN ratio), which is unusually high for its metallicity (Crowther et al. 2003), suggests that the galaxy has experienced a brief but intense galaxy-wide burst of star formation within the last 10 Myr. The starburst was probably triggered by gas falling in from the large, extended H\textsc{i} reservoir (Saito et al. 1992; Wilcots & Miller 1998).

The determination of the distance to IC 10 has been challenging because of its proximity to the Galactic plane (l = 119°, b = −3°). Recently, Vacca et al. (2007) and Sanna et al. (2008) used the tip of the red giant branch to compute a distance of 0.79 and 0.81 Mpc, respectively, to this galaxy. Throughout this paper, we will consider that IC 10 is located at 0.80 Mpc, and hence the spatial scale is 1 arcsec = 3.88 pc.

**Figure 1.** Left: false-colour image of IC 10 obtained combining data provided by Gil de Paz, Madore & Pevunova (2003) in B (blue), R (green) and H\textalpha{} (red) filters. The FOV is 6.8 × 7.4 arcmin\textsuperscript{2}, which covers the majority of the BCDG as it is seen in optical light. Notice the long and extensive ionized gas emission throughout the galaxy. The main star-forming region is shown by a white box. Right: enlargement of the main star-forming region within IC 10 showing the pure H\textalpha{} emission (continuum-subtracted) of the galaxy (Hunter & Elmegreen 2004). Its FOV is 57 × 57 arcsec\textsuperscript{2}. The blue box corresponds to the FOV of the IFU used with PMAS, which has a size of 16 × 16 arcsec\textsuperscript{2} and covers the intense star-forming region [HL90] 111c (Hodge & Lee 1990, see their fig. 2b). The identification of the different H\textsc{ii} regions follows the names given by these authors. The positions of the individual WR stars known in IC 10 (Crowther et al. 2003) are shown by stars. Three of them, [MAC92] 24 A, B and C (yellow stars), are located at the centre of our observed area.
The structure of this paper is the following. In Section 2 we describe the observations and the reduction procedure. Section 3 presents the measurements of the emission lines and how the reddening correction was performed. Section 4 contains the analysis of the ionized gas (extinction, physical conditions, nature of the ionization and chemical abundances) as well as the localization of the WR stars and the determination of the age of the most recent star formation event. Section 5 discusses the two main results found in our analysis: the detection of a probable N and He enrichment in the precise place where the WR features are detected and a warning about the use of empirical calibrations to estimate the oxygen abundances of the ionized gas in nearby galaxies from 2D spectroscopic data. We summarize our conclusions in Section 6.

2 OBSERVATIONS AND DATA REDUCTION

The massive star-forming region [HL90] 111 (Hodge & Lee 1990), also known as [LMR79] #1 (Lequeux et al. 1979), within the starburst galaxy IC 10 was observed on 2007 October 14 at Calar Alto Observatory (Almería, Spain), using the 3.5-m Telescope with the Potsdam Multi-Aperture Spectrometer (PMAS; Roth et al. 2005; Kelz et al. 2006). PMAS is an integral field spectrograph, with a lens array of $16 \times 16$ square elements, connected to a bundle of fibre optics, whose 256 fibres are rearranged to form a pseudo-slit in the focal plane of the spectrograph. We used the standard lens array IFU of $16 \times 16$ arcsec$^2$ field of view (FOV) with a sampling of 1 arcsec which, at the distant to IC 10, provides a spatial sampling of 3.88 pc arcsec$^{-1}$ and a FOV of 62.1 $\times$ 62.1 pc$^2$. Most of the optical range was covered with the V600 grating using two grating rotator angles: $-72^\circ$, covering from 3500 to 5070 Å; and $-68^\circ$, covering from 5700 to 7150 Å. The effective spectral resolution was 3.6 Å. The blue and red spectra have a total integration time of 1800 s in both cases. The position of the IFU covering the massive star-forming region [HL90] 111 is shown in Fig. 1. Its centre has the coordinates $\alpha = 00^h 20^m 27^s 9$, $\delta = 59^\circ17^\prime35.9^\prime$. The reconstruction of the Hα map using our 2D PMAS spectroscopy (Fig. 2) very nicely matches the Hα image provided by Hunter & Elmegreen (2004) and showed in the right-hand panel of Fig. 1. The PMAS data showed two spaxels which poor light transmission, [1, 15] and [8, 16], which we will not consider in our analysis.

The giant H II region [HL90] 111c (see Fig. 1) harbours one of the brightest WR stars in the galaxy, that was named [MAC92] 24 by Massey et al. (1992). Originally identified as a WN star by Richer et al. (2001) because of the detection of the broad He$\alpha$ 4686 emission and the lack of the C IV $\lambda$4650 emission, some authors suggested that this object is a blend of several stars (Massey & Holmes 2002; Crowther et al. 2003; Vacca et al. 2007). In particular, Crowther et al. (2003) noted that there were three closely spaced sources, [MAC92] 24A, B, and C (see Fig. 1), all located within 1–2 arcsec at the south of [HL90] 111c. Later, Vacca et al. (2007) used ground-based laser guide star adaptive optics at the Keck II telescope to resolve [MAC92] 24A in at least three bright, blue sources and [MAC92] 24B into two blue sources, suggesting that there are at least four robust WN candidates in the field. This hypothesis should be confirmed using optical spectroscopy. And, indeed, our 2D PMAS spectra indicate the detection of the blue WR bump precisely at the two spaxels where the WN star candidates [MAC92] 24 B, C should be located. Their position is indicated with a star (spaxel [11, 8], which shows a strong blue WR bump) and a cross (spaxel [11, 9], where the WR bump is also detected but not as intense as in the previous position) in Fig. 2, as we discuss below. The maximum of He$\alpha$ emission provided by our 2D spectroscopic data is located just 1–2 arcsec at the north of the position of the WR stars, and it coincides with the centre of the intense radio-continuum source reported by Yang & Skillman (1993). ([YS93] 001744.6+590101).

Calibration images were obtained during the night: arc lamps for the wavelength calibration and a continuum lamp needed to extract the 256 individual spectra on the CCD. Observations of the spectrophotometric standard stars BD +28° 4211, Feige 110 and G 191-B2B (Oke 1990) were used for flux calibration. The absolute error of this calibration was of the order of 5 per cent. Night was photometric and the typical seeing during the observations was 1 arcsec.

The data were reduced using the IRAF\(^1\) reduction package SPECRED. After bias subtraction, spectra were traced on the continuum lamp exposure obtained before each science exposure, and wavelength calibrated using HgNe arc lamp. The continuum lamp and sky flats were used to determine the response of the instrument for each fibre and wavelength. Finally, for the standard stars we have co-added the spectra of the central fibres and compared with the tabulated 1D spectra.

The effect of the differential atmospheric refraction is negligible because of both the low airmass (between 1.08 and 1.11) in which IC 10 was observed and the short exposure time ($\sim$1 h).

3 LINE MEASUREMENTS

We measured all the emission lines detected in the spectra: hydrogen Balmer lines (H$\alpha$, H$\beta$, H$\gamma$, H$\delta$ and, in some cases, H$\epsilon$ and

\(^1\) IRAF is distributed by NOAO which is operated by AURA Inc., under cooperative agreement with NSF.
for reddening each emission line, following the expression

$$I(\lambda) = \frac{F(\lambda)}{F(H\beta)} \times 10^{(E(B-V)/H\beta)/(\lambda)}$$

being $I(\lambda)$ and $F(\lambda)$ the real and the observed fluxes, respectively, of the emission line and $c(H\beta)$ the reddening coefficient derived from the $H\alpha/H\beta$ ratio. As we describe below (and as it should be expected for IC 10 because of its very low Galactic latitude) the reddening correction is fundamental to get a proper estimation of the line fluxes, and indeed the derived $c(H\beta)$ almost always provides values higher than 1.0 dex.

Unfortunately, the $H\gamma\lambda4358$ telluric emission was completely blended with the faint $[O\,III]\lambda4363$ auroral line, which has a red-shifted wavelength of $\lambda4359$ in IC 10. Using the regions with the faintest ionized gas emission (AP 2, see below), we have estimated an average value of the $H\gamma\lambda4358$ line flux of $1.8 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ for each spaxel. In these resolution elements, and assuming an electron temperature of $T_e \sim 10{,}000$ K, we estimate that the $[O\,III]\lambda4363$ line flux is $\sim 80–100$ times fainter than that measured for the $H\gamma\lambda4358$ line flux and hence completely negligible. However, the contribution of the $[O\,III]\lambda4363$ line to the $H\gamma\lambda4358$ line flux is important in the brightest regions of the nebula. In these cases, and applying the same method, we estimate that $F([O\,III]\lambda4363) \sim 0.4–0.6 \times F(H\gamma\lambda4358)$. The contribution of the auroral line is even more important when integrating the line fluxes of several fibres, as we do in several defined apertures. Hence, we will use the derived average value of the $H\gamma\lambda4358$ line flux to get a estimate of the flux of the $[O\,III]\lambda4363$ line within these areas.

4 RESULTS

The reconstruction of the $H\alpha$ map using our 2D PMAS spectroscopy is shown in Fig. 2. This map corresponds to the area named as [HL90] 111 by Hodge & Lee (1990). We distinguish a very strong star-forming region at the north-west (NW) region ($c$), which has a size of $\sim 10 \times 6$ arcsec$^2$. Other fainter H regions are located at the east (knot $d$) and in the south-west (SW) corner (knot $a$), this last one is only partially covered by our FOV (see Fig. 1). An important feature is a hole located at the south of the brightest star-forming region. Indeed, there is an arc-like filament of ionized gas (knot $e$, following Hodge & Lee 1990) connecting the SW tip of the brightest star-forming area ($c$) with the H region located at the east ($d$). The minimum of $H\alpha$ emission (the hole) is located between these three structures.

We have integrated the spectra within several regions to analyse in detail the properties of the ionized gas and to maximize the S/N of the 1D spectra. Fig. 2 shows the position of these regions: AP 1 (which corresponds to the brightest star-forming region, [HL90] 111c), AP 2 (which corresponds to the hole of $H\alpha$ emission), AP 3 (which corresponds to [HL90] 111d) and AP 4 (which integrates the spectra of the two spaxels where the WR features are detected). For these four regions, we measured all the line fluxes following the same procedure explained before. We also carefully analysed two individual fibres: #90 (spaxel [11, 10]), where a tentative detection of the nebular $He\,II\lambda6686$ line is found, and #92 (spaxel [11, 13]), which corresponds to the maximum in the $H\alpha$ emission and hence to the fibre where emission lines have the best S/N.

Because of the stacking of the spectra, some emission lines that were not easily observed in the individual spaxels (i.e. $H\beta$, $H\alpha$, $Ne\,II\lambda3869$, $Ne\,II\lambda3967$,$He\,I\lambda4471$) are now clearly distinguished. That allowed us to perform a more accurate determination of the reddening coefficient within these areas.
considered all available H I Balmer line ratios (Hα/Hβ, Hβ/γ, Hβ/Hδ, and also Hβ/Hγ in the brightest region) and applied the formalism explained in López-Sánchez (2006) and López-Sánchez & Esteban (2009) to simultaneously derive c(Hβ) and the equivalent width of the absorption in the H I lines, \( W_{\text{abs}} \), which we assumed to be the same for all H I Balmer lines. Table 1 shows the determined line intensity ratios and their associated errors, as well as the adopted \( f(x) \) of each emission line, measured for the total integrated spectrum, the four regions we have carefully analysed, and fibres #90 and #92. In this table we also include other important quantities such as the size of the extracted aperture, the observed H β flux (uncorrected for extinction), the adopted values of c(Hβ) and \( W_{\text{abs}} \), and the equivalent widths of the H I Balmer lines. Colons indicate errors of the order or larger than 40 per cent. As explained before, the contribution of the Hγ lines to \( f(x) \), \( W_{\text{abs}} \), and the number of fibres used to get the integrated spectrum of the region.

The Hα map obtained using 2D spectroscopy allows us to determine the total luminosity and the mass of the ionized gas within these regions. The extinction-corrected Hα flux was determined considering

\[ I(\text{H\alpha}) = F(\text{H\alpha}) \times 10^{0.4 \log L(\text{H\alpha})} = F(\text{H\alpha}) \times 10^{4.8 \log L(\text{H\alpha})/2.5}. \]

(2)

The value of the extinction in the Hα line, \( A_{\text{H\alpha}} \), was computed in each region considering the value of the \( f(\text{H\alpha}) \) provided by the Cardelli et al. (1989) extinction law and the (c(\text{H\beta})) derived in our analysis, \( A_{\text{H\alpha}} = 1.755 \times c(\text{H\beta}) \), and it is tabulated in Table 1. The total Hα luminosity was computed assuming a distance to IC 10 of 0.8 Mpc, the uncertainty of \( L(\text{H\alpha}) \) also includes the uncertainty in the distance. We estimate a total Hα luminosity of \((1.185 \pm 0.064) \times 10^{39}\) erg s\(^{-1}\). Using the Calzetti et al. (2007) calibration between \( L(\text{H\alpha}) \) and the star formation rate (SFR) we derive SFR\(_{\text{H\alpha}} = (6.28 \pm 0.34) \times 10^{-3} \text{ M}_\odot \text{ yr}^{-1}\). This value corresponds to an SFR density of \( 1.64 \times 0.09 \text{ M}_\odot \text{ pc}^{-2} \) and confirms the starburst activity that the centre of IC 10 is experiencing.

Finally, the mass of the ionized gas, \( M_{\text{ion}} \), was computed using the expression provided by Pérez-Montero (2002), \( M_{\text{ion}} = 1.485 \times 10^{-35} I(\text{H\alpha}) \times (n_e/100) \), where \( n_e \) is the electron density (in cm\(^{-3}\)) derived from our spectroscopic data (which was always

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100 cm\(^{-3}\)) and the result is obtained in solar masses. The derived values of \(L(\text{H}\alpha)\) and \(M_{\text{H}\alpha}\) of each region are also included in Table 1. We estimate a total ionized gas mass of \((1.76 \pm 0.10) \times 10^6\ M_\odot\) within all the observed field. Table 1 also lists the ionized gas mass per surface area, \(M_{\text{H}\alpha}/\text{area}\). It has a minimum value of 1.10 \(M_\odot\) pc\(^{-2}\) in the hole but it reaches the maximum values in the strong star-forming region, which has \(M_{\text{H}\alpha}/\text{area} = 15.3\ M_\odot\) pc\(^{-2}\).

### 4.1 Reddening map

Left-hand panel of Fig. 4 shows the map of the reddening coefficient derived in IC 10 using the \(\text{H}\alpha/\text{H}\beta\) ratio. \(c(\text{H}\beta)\) has values between 1.0 and 1.8 dex. These values correspond to an extinction in the \(V\) band, \(A_V\), between 2.15 and 3.86 mag or, equivalently, a colour excess, \(E(B - V)\), between 0.69 and 1.25 mag. The integrated value of the extinction in the \(V\) band is \(A_V = 3.05 \pm 0.11\) mag. These values nicely match previous values of the extinction given in the literature (e.g. Lee, Freedman & Madore 1993; Vacca et al. 2007; Lozinskaya et al. 2009). These values confirm the high extinction existing in the direction to IC 10, but because of its very low Galactic latitude we know that a very important fraction of the observed extinction is due to the Galactic ISM. In any case, assuming that the Galactic extinction is mainly constant in all the observed region; we appreciate that the dust within the star-forming region has a rather inhomogeneous distribution. In particular, we note the lower values of \(c(\text{H}\beta)\) are located near the WR stars, at the south-east (SE) of the brightest \(\text{HI}\) region, that show \(c(\text{H}\beta)\) between 1.0 and 1.3 dex. The maximum values of the reddening coefficient are found at the NW of the brightest star-forming region, which has values between 1.5 and 1.8 dex. Other areas (at the south of the hole and in the knot \(a\) at the SW corner) also show a high extinction. The average value we determine for all the observed region is \(c(\text{H}\beta) = 1.42 \pm 0.05\) dex. This peculiar distribution suggests that the dust around the massive stars has been evacuated by interstellar winds and/or radiation pressure or partially destroyed. Although this effect has not been investigated in detail, there are indications of decreasing values of the extinction around young stars in the Orion Nebula cluster (Hillenbrand 1997).

We compared the reddening coefficient derived from the \(\text{H}\alpha/\text{H}\beta\) ratio with that estimated using the \(\text{H}\gamma/\text{H}\beta\) ratio in those fibres in which \(\text{H}\gamma\) is properly measured (52 per cent of the spaxels). The left-hand panel of Fig. 5 plots the \(c(\text{H}\beta)\) values derived in each case. As we see, although the correspondence between both values is relatively good, the \(c(\text{H}\beta)\) derived from the \(\text{H}\gamma/\text{H}\beta\) ratio is systematically lower than that computed using the \(\text{H}\alpha/\text{H}\beta\) ratio. This effect is consequence of the \(\text{HI}\) Balmer line absorption of the underlying stellar population. The right-hand panel of Fig. 5 plots the \(c(\text{H}\beta)\) values derived in each case when considering a \(\text{HI}\) Balmer line absorption of \(W_{\text{abs}} = 2.2\ \AA\), the value we derived iteratively for the integrated spectrum of the observed field (see Table 1). Indeed, the correspondence between both \(c(\text{H}\beta)\) is much better when \(W_{\text{abs}}\) is taken into account, although the dispersion of the data is slightly higher because of the higher uncertainty in both the \(\text{H}\gamma\) fluxes and equivalent widths.

### 4.2 Physical conditions of the ionized gas

Because of the faintness of the auroral lines and the contamination of the \(\text{H}\gamma\) \(\lambda 4358\) telluric line, it was not possible to derive a temperature map from our PMAS data. We used the \([\text{S}\ ii]\) \(\lambda 6716/\lambda 6731\) ratio to derive a bidimensional map of \(n_e\), assuming a \(T_e = 10500\ \text{K}\) (the electron temperature derived for the ionized gas, see below). Lower values of the \([\text{S}\ ii]\) \(\lambda 6716/\lambda 6731\) ratio indicate higher values in \(n_e\). We used the \textsc{temden} task of the \textsc{nebular} package of \textsc{iraf} (Shaw & Dufour 1995) with updated atomic data (see García-Rojas et al. 2005). This map is shown in the right-hand panel of Fig. 4. Purple and blue points indicate the places where the electron density is in the low limit, \(n_e \lesssim 100\ \text{cm}^{-3}\) \([\text{S}\ ii]\) \(\lambda 6716/\lambda 6731\) ratios between 1.40 and 1.32. As we see, these colours are the predominant in the observed region. However, we note some places with electron densities between 100 and 400 cm\(^{-3}\) \([\text{S}\ ii]\) \(\lambda 6716/\lambda 6731\) ratios between 1.32 and 1.10. Hence, these regions have a higher gas density than that found in the surrounding ISM. It is important to note that the three regions with the highest electron density are precisely located in the places where we find the maximum of the reddening coefficient (left-hand panel in Fig. 4).
Table 2. Physical conditions and chemical abundances of the ionized gas for the regions analysed in IC 10 using our PMAS data. Three dots indicate that the abundance could not be derived because of the non-detection of some emission lines.

| Region | [HL90] 111 | AP1 (c) | AP2 (hole) | AP3 (d) | AP4 (WR 24) | Fibre 90 | Fibre 92 |
|--------|------------|---------|------------|---------|-------------|----------|---------|
| $T_e$ [O III] [K] | 10600 ± 600 | 10600 ± 600 | 10500 ± 1000 | 10700 ± 800 | 10500 ± 1000 | 10500 ± 1000 | 10500 ± 1000 |
| $T_e$ [O III] [K] | 10400 ± 400 | 10400 ± 400 | 10400 ± 700 | 10500 ± 600 | 10400 ± 700 | 10400 ± 700 | 10400 ± 600 |
| $n_e$ [cm$^{-3}$] | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 12+log(O$^+$/H$^+$) | 7.96 ± 0.12 | 7.78 ± 0.10 | 7.89 ± 0.24 | 7.84 ± 0.12 | 7.74 ± 0.19 | 7.70 ± 0.20 | 7.65 ± 0.13 |
| 12+log(O$^{++}$/H$^+$) | 7.96 ± 0.06 | 8.03 ± 0.07 | 7.94 ± 0.10 | 8.01 ± 0.07 | 8.02 ± 0.08 | 8.05 ± 0.09 | 8.07 ± 0.08 |
| 12+log(O/H) | 8.26 ± 0.09 | 8.22 ± 0.08 | 8.22 ± 0.17 | 8.23 ± 0.09 | 8.21 ± 0.10 | 8.21 ± 0.13 | 8.21 ± 0.09 |
| log(O$^{++}$/O$^+$) | 0.00 ± 0.13 | 0.25 ± 0.12 | 0.04 ± 0.25 | 0.17 ± 0.14 | 0.28 ± 0.20 | 0.36 ± 0.21 | 0.42 ± 0.15 |
| 12+log(N$^+$/H$^+$) | 6.54 ± 0.05 | 6.33 ± 0.05 | 6.49 ± 0.15 | 6.43 ± 0.05 | 6.49 ± 0.10 | 6.24 ± 0.11 | 6.19 ± 0.06 |
| 12+log(N/H) | 6.84 ± 0.08 | 6.78 ± 0.09 | 6.81 ± 0.20 | 6.90 ± 0.10 | 6.95 ± 0.17 | 6.75 ± 0.18 | 6.76 ± 0.12 |
| log(N/O) | −1.42 ± 0.12 | −1.45 ± 0.11 | −1.41 ± 0.24 | −1.41 ± 0.13 | −1.26 ± 0.20 | −1.46 ± 0.21 | −1.45 ± 0.15 |
| 12+log(S$^+$/H$^+$) | 5.77 ± 0.04 | 5.50 ± 0.04 | 5.75 ± 0.09 | 5.67 ± 0.05 | 5.54 ± 0.09 | 5.41 ± 0.09 | 5.40 ± 0.05 |
| log(S$^+$/O$^+$) | −2.19 ± 0.16 | −2.28 ± 0.14 | −2.14 ± 0.33 | −2.17 ± 0.17 | −2.20 ± 0.28 | −2.29 ± 0.29 | −2.25 ± 0.18 |
| log(N$^+$/S$^+$) | 0.77 ± 0.09 | 0.83 ± 0.09 | 0.74 ± 0.24 | 0.76 ± 0.10 | 0.95 ± 0.19 | 0.83 ± 0.20 | 0.79 ± 0.11 |
| 12+log(Ne$^++$/H$^+$) | 7.50 ± 0.16 | 7.45 ± 0.19 | ... | 7.50 ± 0.25 | ... | ... | 7.38 ± 0.21 |
| 12+log(Ne/H) | 7.80 ± 0.16 | 7.65 ± 0.18 | ... | 7.73 ± 0.25 | ... | ... | 7.52 ± 0.21 |
| log(He/O) | −0.46 ± 0.23 | −0.58 ± 0.24 | ... | −0.51 ± 0.30 | ... | ... | −0.69 ± 0.27 |
| 12+log(He$^+$) | 5.90 ± 0.08 | 5.92 ± 0.09 | 5.81 ± 0.16 | 5.94 ± 0.10 | 5.90 ± 0.13 | 5.90 ± 0.13 | 5.96 ± 0.09 |
| log(He$^+$/O$^+$) | −2.06 ± 0.14 | −2.11 ± 0.16 | −2.13 ± 0.26 | −2.07 ± 0.17 | −2.12 ± 0.21 | −2.15 ± 0.22 | −2.11 ± 0.17 |
| 12+log(He$^+$) | 10.99 ± 0.04 | 10.98 ± 0.03 | 11.03 ± 0.11 | 10.99 ± 0.04 | 11.09 ± 0.05 | 10.97 ± 0.09 | 10.99 ± 0.03 |

For the integrated spectra, we derived the flux of the auroral [O III] λ4363 line by subtracting the expected flux of the telluric Hg I λ4358 line considering the number of fibres used in each region. We then applied the TEMDEN task of the NEBULAR package of IRAF to derive the $T_e$[O III] in each region. For AP 2, which integrates the flux of the faintest regions of the nebula, the value derived for the [O III] λ4363 line is just a residual value. In all cases, $T_e$[O III] is around 10500 K, in agreement with previous results found in IC 10 (i.e. Garnett 1990; Crowther et al. 2003; Lozinskaya et al. 2009), so we are quite confident in the validity of our decontamination of Hg I emission. Using the relation between $T_e$[O III] and $T_e$[O II] provided by Garnett (1992), $T_e$[O III] = 0.7 × $T_e$[O II]+3000, we have estimated the electron temperature for the low-ionization potential ions. We compile the electron temperatures derived in each of the regions in Table 2. This table also lists the electron density computed for each region using the [S II] λ6716/λ6731 ratio. In all cases, this ratio provided a density which was below the low-density limit, $n_e < 100$ cm$^{-3}$, and hence we always considered $n_e = 100$ cm$^{-3}$.

4.3 Nature of the ionization

Fig. 6 shows the emission line ratio maps we obtained for the analysed region in IC 10. All maps have been corrected for reddening using the $c$(Hβ) value derived from the Hα/Hβ ratio. We show the...
Figure 6. Emission line ratio maps with Hα contours overlaid into the IC 10 PMAS field of: (top left) [O III] λ5007/Hβ; (top right) He I λ5876/Hα; (bottom left) [N II] λ6583/Hα; (bottom right) [S II] λλ6716, 6731/Hα. All maps have been corrected for reddening using the c(Hβ) value derived from the Hα/Hβ ratio. Symbols are the same that in Fig. 2.

maps corresponding to [O III] λ5007/Hβ, [N II] λ6583/Hα, ([S II] λ6716+λ6731)/Hα and He I λ5876/Hα. White colours indicate regions in which the studied emission line was not detected or it was too noisy.

As we see, the maps are showing the ionization structure of the giant H II regions in the centre of IC 10. That is specially evident in the brightest star-forming region [HL90] 111c and in the H II region located at the SE, [HL90] 111d, both show the maxima of the [O III] λ5007/Hβ ratio at their centres, while the maxima of the low-ionization potential ion ratios is located surrounding those central bright areas. This effect is clearly noticed in the [O III] λ5007/O II λ3727 ratio map plotted in Fig. 7, which shows the higher values at the centre of the strong star-forming regions. This result is very important and should be taken into account, as we will see below, when using empirical calibrations to get the chemical abundance of the ionized gas. It is also interesting to note that the highest values of the [O III] λ5007/Hβ ratio is close to the maximum of the Hα emission, but they are not completely coincident.

We have also analysed the diagnostic diagrams plotting two different excitation line ratios for classifying the excitation mechanism of the ionized gas, as initially proposed by Baldwin, Phillips & Terlevich (1981) and Veilleux & Osterbrock (1987). Fig. 8 plots the typical [O III] λ5007/Hβ versus [N II] λ6583/Hα and [O III] λ5007/Hβ versus ([S II] λλ6716+λ6731)/Hα diagrams for all the spaxels for which we have a good measurement of these lines. In these diagnostic diagrams, H II regions and starburst galaxies lie within a narrow-band, but when the gas is excited by shocks, accretion discs or cooling flows (in the case of active galactic nuclei or low-ionization nuclear emission-line regions), its position is away from the locus of H II regions. We used the analytic relations given by the photoionized models provided by Dopita et al. (2000) for extragalactic H II regions (that assume instantaneous star formation within star-forming regions) and the Kewley et al. (2001) models for starburst galaxies (which consider continuous star formation and more realistic assumptions about the physics of starburst galaxies). In both cases, photoionization models with very different
4.4 Chemical Abundances

Because of the lacking of an individual estimation of the electron temperature, we are not able to map the chemical abundances using the direct method. We will discuss in Section 5.2 the effects of using empirical calibrations to map the chemical abundances of an H II region or a starburst galaxy using 2D spectroscopy. Here we analyse the chemical abundances obtained from the integrated spectra of the areas we described in Fig. 2.

We used the IRAF package nebular to derive ionic abundances of N+, O+, O2+, S2+, Ne+, and Ar+2 from the intensity of collisionally excited lines. We assumed a two-zone scheme for deriving the ionic abundances, adopting Te([O III]) for the high ionization potential ions O2+, Ne+, and Ar+2, and Te([O II]) for the low ionization potential ions O+ and S+. The errors in the ionic abundances have been calculated as a quadratic sum of the individual contributions of errors in flux, ni, and Te.

To derive He+/H+, we used three observed lines of He I at λλλ 4471, 5876, and 6678, weighted by 1:3:1. Case B emissivities for the Te([O III]) and ni, assumed for each region, were taken from the collisionless (low-density limit) calculations by Bauman et al. (2005) using an online available code. The collisional recombination contribution was estimated from Kingdon & Ferland (1995), using the interpolation formula provided by Porter, Ferland & MacAdam (2007). The effective recombination coefficients for H+ were taken from Storey & Hummer (1995).

We computed the total abundances of O and N, adopting O/H = O+/H+ + O2+/H+ to determine the total oxygen abundance and the standard ionization correction factor (ICF) by Peimbert & Costero (1969), N/O = N+/O+, to compute the total nitrogen abundance. For those regions in which we have a detection of the [Ne III] lines, we computed the total neon abundance applying the ICF proposed by Peimbert & Costero (1969), Ne/O = Ne+2/O+2.

We derive a total O abundance of 12+log(O/H) = 8.26 ± 0.09 for all the observed region. The derived N/O and Ne/O ratios, log(N/O) = −1.42 ± 0.12 and log(Ne/O) ∼ −0.42, are the typical values expected for a galaxy with the metallicity of IC 10 (Izotov & Thuan 1999; Izotov et al. 2004; López-Sánchez & Esteban 2010b). These results are very similar in the regions AP 1 ([HL90] 111c, the brightest star-forming region), AP 2 (the Hα hole) and AP 3 ([HL90] 111d), but they slightly differ in the AP 4 region, which only considers the emission in those two fibres where the WR stars are detected. We will discuss this intriguing result in Section 5.1.

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2 Available at http://www.pauKy.edu/~reporter/j-resolved
4.5 Wolf–Rayet content

We have clearly detected the blue WR bump in two adjacent fibres (spaxels [11, 8] and [11, 9]). This position coincides with one of the WR stars catalogued within [HL90] 11c (see Fig. 1, right) in the most recent WR stars catalogue of IC 10 (Crowther et al. 2003), [MAC92] 24C. We have also a tentative detection of the nebular He II λ4686 line in spaxel [11, 10], which corresponds to the position of the WR [MAC92] 24B. However, we do not observe any WR feature at the position of [MAC92] 24A (spaxel [10, 10]) or in the position of RSMV 23 (spaxels [2, 14] and [2, 15]), although the S/N of this last region is relatively low.

We have added the spectra of the two spaxels where the blue WR bump is observed (AP 4) and carefully analysed the properties of the integrated spectrum. The emission line fluxes are listed in Table 1, and the derived physical and chemical properties of the ionized gas are given in Table 2. For comparison, we have also analysed two nearby fibres, the adjacent position to the detection of the blue WR bump (F90, which corresponds to the spaxel [11, 10], where there is a tentative detection of the nebular He II λ4686 line), and the fibre with the maximum of the Hα emission (F92, which corresponds to the spaxel [11, 12]).

In our case, the blue WR bump we detect in AP 4 is essentially constituted by the stellar, broad, He II λ4686 emission feature. Fig. 9 shows a detail of this spectrum in the 4620–4750 Å range, showing a prominent bump. We do not detect the CIII/CIV λ4650 or the CIV λ5808 (the red WR bump) and hence we agree with the results found by other authors (Crowther et al. 2003; Vacca et al. 2007) that the observed WR features are originated by a WN star. Both the strength of the broad He II λ4686 emission and the absence of the N v λ4604 emission indicate that this is a late-type WN (WNL) star.

We have followed the method described in López-Sánchez & Esteban (2010a) to estimate the flux of the blue WR Bump. We fitted a broad and a narrow Gaussian for the stellar and nebular He II λ4686 lines. Fig. 9 shows the result of this fitting, including the residual spectrum after subtracting the best-fitting model to the observed spectrum. The best-fitting model values are FWHM$_{\text{He II broad}} = 8.12 \pm 0.76$ Å, F$_{\text{He II broad}} = (8.76 \pm 0.79) \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ for the broad component and FWHM$_{\text{He II narrow}} = 5.4 \pm 0.9$ Å, F$_{\text{He II narrow}} = (6.1 \pm 1.0) \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ for the narrow component.

Using the reddening coefficient derived for AP 4 and its relation with the extinction at λ4686 [assuming the Cardelli et al. (1989) extinction law with R$_{V} = 3.1$, A$_{\lambda 4686} = 2.625$E(B/V)] and considering the distance to IC 10, we derive a total luminosity of L$_{\text{He II broad}} = (1.35 \pm 0.17) \times 10^{36}$ erg s$^{-1}$ for the broad He II λ4686 emission. We can use this value to compute the total number of WR stars in the burst. For this, and following López-Sánchez & Esteban (2010a), we consider a metallicity-dependence of the WR luminosities. Using the relation between the luminosity of the He II λ4686 line and the oxygen abundance (their equation 7), we estimate that a single WNL with the metallicity found in IC 10 [which we assume to be 12+log(O/H) = 8.25], has a luminosity of L$_{\text{He II}}$(He II λ4686) = 1.27 \times 10^{36}$ erg s$^{-1}$. Hence, the blue WR bump observed in this position of IC 10 is consistent with being produced by a single WNL star and not by four, as Vacca et al. (2007) suggested from their optical/NIR images. This conclusion is essentially the same in the case of considering the luminosity of a WN star with a solar metallicity to the broad λ4686 flux, L$_{\text{He II}}$(He II λ4686) = 1.6 \times 10^{36}$ erg s$^{-1}$ (Crowther & Hadfield 2006), which gives 1.19 WNL stars within this starburst.

To estimate the WR/(WR+O) ratio, we also follow the prescriptions given by López-Sánchez & Esteban (2010a). We determine this ratio within the intense star-forming region. The total number of ionizing photons is $Q_{\text{ion}} = L_{\text{UV}}/4.76 \times 10^{43} = 2.84 \times 10^{46}$ s$^{-1}$, and the $\eta(t) = 0.77$ parameter (Vacca & Conti 1992; Vacca 1994; Schaerer & Vacca 1998) which depends on the age of the burst, is $\eta \sim 1$. Hence, applying equation (10) of López-Sánchez & Esteban (2010a) considering $N_{\text{WNL}} = 1$ and $N_{\text{WCE}} = 0$, we estimate a total number of O stars of 26 and a WR/(WR+O) ratio of 0.037. This value agrees with that determined in other WR galaxies with a similar oxygen abundance (see fig. 5 in López-Sánchez & Esteban 2010a).

Fibre 90 (spaxel [11, 10]) does not only shows a tentative detection of the nebular He II λ4686 line, but it also shows a clear broad Hα component underlying the narrow, nebular Hα emission. These kinds of features are rather common in extragalactic H II regions (e.g. Firpo, Bosch & Morrell 2005; Firpo et al. 2010) and starburst galaxies (e.g. Méndez & Esteban 1997; Homeier & Gallagher 1999). Recent detailed analyses of nearby starbursts using IFU spectroscopy [e.g. NGC 1569, Westmoquette et al. (2007a); M 82, Westmoquette et al. (2007b, 2009); Mkn 996, James et al. (2009)] are also revealing the existence of broad components underlying the bright nebular lines that are originated in turbulent movements and shocks of the ionized gas. Our analysis of the emission-line profiles within the centre of NGC 5253 (López-Sánchez et al. 2007) also indicated that they were composed by a narrow and a broad components (see also Monreal-Ibero et al. 2010). Furthermore, the analysis of their chemical abundances revealed that the broad component of the knot B of NGC 5253 seems to contain the localized N enrichment in this area of the galaxy (see their section 9).
and their table 10). Very different abundance results between the individual line components were recently reported in Mkn 996 (James et al. 2009). Because of the lacking of spectral resolution, we cannot do this analysis here. However, we have followed the same procedure used before to fit the nebular and stellar He II λ4686 lines to fit the narrow and broad components of the Hα line in this fibre. We estimate that the extinction-corrected flux contained in the broad Hα component is $(8.3 \pm 0.7) \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$, which is $\sim$11 per cent of the flux measured in the narrow line. This value indicates that this component contains a mass of about $\sim$9.5 $M_{\odot}$. The estimated FWHM of the broad Hα component is $\sim$40 Å, which indicates a velocity of $\sim$1830 km s$^{-1}$. This high value suggests that the flow should be related to a remnant of a recent SN explosion that has still not produced an observable chemical enrichment.

4.6 Age of the starburst

Fig. 10 shows the map of the equivalent width of the Hα emission, $W_{H\alpha}$, derived in the intense star-forming region [HL90] 111 from our PMAS data. As we see, the maximum values of $W_{H\alpha}$ are found at the west of the central star-forming region, which shows $W_{H\alpha}$ between 850 and 1000 Å. Using the STARBURST 99 stellar population synthesis model (Leitherer et al. 1999) with an instantaneous burst with a Salpeter initial mass function slope ($\alpha = 2.35$) with $M_{\text{max}} = 100 M_{\odot}$ and $Z = 0.008 Z_{\odot}$ [which corresponds to an oxygen abundance of $12+\log(O/H) = 8.26$, considering a solar oxygen abundance of $12+\log(O/H) = 8.66$ (Asplund, Grevesse & Sauval 2005)], we derive an age between 3.3 and 4.2 Myr for the most recent starburst. The eastern areas of this intense star-forming region show values around $W_{H\alpha} \sim 600$–700 Å, which are translated to an age of $\sim$4.7 Myr. Similar values are found at the central region of the smaller star-forming region at the east (knot d). The arc-like structure at the south has $W_{H\alpha} \sim 300$–500 Å. Although the presence of Hα absorption may underestimate the actual equivalent widths of the emission lines (and hence the age of the last star formation event is overestimated), we consider that in our case their effect in $W_{H\alpha}$ is very small because of the strength of this emission line. Indeed, the average value of $W_{H\alpha}$ derived here (see Section 4.1) is only 2.2 Å. However, as we discussed before, the effect of the H1 line absorption should be considered when studying the rest of the Balmer lines and, particularly, to derive a more appropriate value of the reddening coefficient.

It is interesting to note that the places in which the WR features are detected have relatively low values of $W_{H\alpha} \sim$100 Å, which yields to an age of $\sim$6.2 Myr for the most recent star formation event. That age is older than that we should expect for a WR star, as the most massive, luminous and hot O stars evolve to the WR phase between 2 and 5 Myr since their birth, spending only some few $10^4$ yr before they explode as Type Ibc supernovae (Meynet & Maeder 2005). Hence, the star formation activity may not be strictly instantaneous but it has probably had some continuous rate. Maybe, the detected WR star was formed somewhat later after the majority of the stellar population in the area. Furthermore, as we are considering very small spatial scales (1–3 arcsec $\sim$3.9–11.6 pc), the WR star may currently be some distance from its birth place.

5 DISCUSSION

5.1 A possible localized chemical pollution by a Wolf–Rayet star?

The only confirmed case of localized chemical pollution by WR stars in a starburst region to date is the centre of the BCDG NGC 5253 (Walsh & Roy 1989; Kobulnicky et al. 1997; López-Sánchez et al. 2007). This object shows a clear enhancement in the N/H ratio (and also in the He/H ratio) in a small region, which is consistent with the chemical pollution expected by the contribution of just a few (1–2) evolved (WR) massive stars (López-Sánchez et al. 2007). There are some studies that also suggest that starbursts in which WR stars are detected may show an enhancement in their N/O ratio (Pustilnik et al. 2004; Brinchmann, Kunth & Durret 2008; James et al. 2009; López-Sánchez & Esteban 2010b). Recent 2D spectroscopical data (Pérez-Montero et al., in preparation) also report very high N/O ratios in BCDGs with WR stars. However, in these cases the chemical pollution by the WR stars detected in the central region seems not to be able to explain the large enhancement of nitrogen found throughout the BCDG. Similarly, Amoríz, Pérez-Montero & Vilchez (2010) used SDSS data to find that, at a given metallicity, the so-called green pea galaxies display systematically large N/O ratios compared to normal galaxies, but these spectra are not deep enough to detect WR features.

In this case, our 2D spectroscopical PMAS maps of the strong star-forming region [HL90] 111 within IC 10 suggests the detection of a localized high N/O ratio at the positions where the WR features are detected (AP 4). Fig. 11 shows the [N II] $\lambda6583$/[S II] $\lambda6717$ + [S II] $\lambda6731$ line intensity ratio map. Because of the faintness of the [O II] $\lambda3727$ doublet, the [N II] $\lambda6583$/[O II] $\lambda3727$ line intensity ratio map shows a very low S/N in a large number of spaxels where the surface brightness of the nebular gas is low, and hence it is useless for our purposes. Considering only the spaxels with higher S/N, the average value of the [N II] $\lambda6583$/[O II] $\lambda3727$ ratio is $\sim$0.07. Spaxel [11, 8], labelled with a cross in all maps and where some He II $\lambda4686$ emission is observed, has a very uncertain detection of the [O II] $\lambda3727$ doublet. However, spaxel [11, 9] (labelled with a star and where the highest He II $\lambda4686$ emission is observed) seems to have a slightly higher [N II] $\lambda6583$/[O II] $\lambda3727$ ratio, $\sim$0.10, but because of the high uncertainty this value is not

![Figure 10. Map of the equivalent width of the Hα emission, $W_{H\alpha}$, derived in the intense star-forming region [HL90] 111 (Hodge & Lee 1990) from our PMAS data. The contours of the Hα emission are overlaid. Symbols are the same that in Fig. 2.](https://academic.oup.com/mnras/article-abstract/411/3/2076/973571/figure-10)
significant. On the other hand, the $[\text{N} \, \text{II}] \lambda 6583/(\text{[S} \, \text{II}] \lambda 6717 + \lambda 6731)$ ratio, which is well measured in almost all spaxels, indicates a rather clear increase of its average value ($\sim$0.85) precisely at the two spaxels where WR features are detected. Indeed, spaxels [11, 8] and [11, 9] show a $[\text{N} \, \text{II}] \lambda 6583/(\text{[S} \, \text{II}] \lambda 6717 + \lambda 6731)$ ratio of 1.11 and 1.01, respectively, with a typical uncertainty of $\pm 0.12$.

It is interesting to note that the $\text{He}^+ \lambda 5875/\text{H} \alpha$ ratio map (top right panel in Fig. 6) also shows an enhancement of the emission at the same position. The average $\text{He}^+ \lambda 5875/\text{H} \alpha$ ratio is $\sim 0.046$ but spaxels [11, 8] and [11, 9] have a ratio of 0.071 and 0.058, respectively, with an error of only $\pm 0.007$. It is possible that we are detecting at this position a localized enhancement of both nitrogen and helium, which, if true, is very probably connected with the detection of WR features in those same spaxels.

We further investigate this very intriguing result via the careful analysis of the chemical properties of the integrated spectrum obtained adding both spaxels (AP 4). As control, we also study the adjacent spaxel [11, 10] (Fibre 90), which has enough S/N to perform such analysis. Table 2 compiles all the chemical abundances and ratios derived for these two regions. As we see AP 4 possesses, systematically, higher N/O, $\text{N}^+$/S$^2$ and He$^+$/H$^+$ ratios ($\sim$1.26, 0.95 and 11.09, respectively) than those values derived for any other aperture or spaxel, which have average values of $\sim$1.44, 0.79 and 10.99, respectively. We also note that the S$^+/\text{O}^+$ (two elements of similar nucleosynthetic origin) ratio remains practically the same for all regions including AP 4, showing a average value of $\sim 2.22$.

Hence, although we cannot definitively confirm that there is a localized chemical pollution in nitrogen in those two spaxels because of the relatively high uncertainties, all evidence points towards it. We must emphasize that the helium enrichment is indeed confirmed within the errors, because the average value of $12+\log$(He$^+$/H$^+$) is 10.99 $\pm 0.03$ while that measured in AP 4 is 11.09 $\pm 0.05$.

With the data collected in Tables 1 and 2 we can make a rough estimation of the mass of newly created He and N (stellar yield) necessary to produce the observed overabundances in region AP 4. These yields have been computed considering the He and N abundances of region AP 1 as reference. Therefore, we have assumed that the initial abundances of the ionized gas at AP 4 are those measured at AP 1 and that AP 4 has suffered a localized and very recent increment of the He/H and N/H ratios. Finally, the empirical stellar yields have been obtained multiplying those He/H and N/H increments by the mass of ionized gas derived for AP 4. The computed stellar yields are 28 $\pm$ 16 and 0.013 $\pm$ 0.013 $M_\odot$ for He and N, respectively. These numbers can be compared with those given in table 12 of López-Sánchez et al. (2007), that includes the yields determined for regions A and B of NGC 5253 as well as theoretical ones from stellar evolution models and empirical determinations for ring nebulae around Galactic WR stars. The yields found in [HL90] 111 (although uncertain) are roughly consistent with the scenario of chemical pollution by the ejecta of a very small number of WR stars. The amount of He appears to be rather high, in fact the ratio of He and N stellar yields is about 2150, 10 times higher than in the objects included in the aforementioned table of López-Sánchez et al. (2007).

We must say that it is not the first time that a region with a probably high N/O is reported in IC 10. Magrini & Gonçalves (2009) used Gemini North Multi-Object Spectrograph to map the H$ \beta$ regions and planetary nebulae in the central 5.5 $\times$ 5.5 arcmin$^2$ of IC 10. Their data suggested that the H$ \beta$ region [HL90] 120, with an oxygen abundance of $12+\log$(O/H) $\sim$ 8.18, has a N/O ratio of $\sim$0.48 dex, but the other H$ \beta$ regions (which have an oxygen abundance between 8.0 and 8.7) show N/O ratios of $\sim$1.25. However, their data have high uncertainties (the majority of N/O values agree within the errors, see their fig. 2), and hence this result should be also confirmed. Furthermore, all the N/O ratios these authors derived for their analysed H$ \beta$ regions within IC 10 seem to be higher than those expected for their oxygen abundance.

As Magrini & Gonçalves (2009) pointed out, the H$ \beta$ region [HL90] 120 contains four known WR stars within 20 arcsec from its centre, and hence the origin of the tentative high N/O ratio may be some of these WR stars. In our case, we note that our possible detection of a high N/O and He/H ratios are found exactly at the same position where the WR features are located, indicating that, if real, this chemical pollution is indeed very localized ($\sim$2 arcsec $\sim$7.8 pc) and therefore it should be very difficult to detect in fainter and distant galaxies.

Some studies affirm that the more or less low and constant values of the N/O ratio reported in blue compact galaxies (BCGs) is a consequence of the fact that anything ejected by massive stars (whether oxygen by Type II supernovae or nitrogen in the winds of WR stars) is too hot to be immediately incorporated to the ISM, and it needs to cool before mixing with the existing nebular gas and appears in the optical spectrum (e.g. Kobulnicky & Skillman 1996, 1997, 1998; Kobulnicky et al. 1997; Henry et al. 2000; Pilyugin, Thuan & Víchez 2003; van Zee & Haynes 2006; Magrini & Gonçalves 2009; Lagos et al. 2009). However, as previously suggested by Pustilnik et al. (2004) and López-Sánchez et al. (2007), the presence of localized chemical enrichment in very young starbursts indicates that the time-scale of the process should be very short. This agrees with the enrichment pattern observed in Galactic WR ring nebulae (Esteban et al. 1992). The statistical analysis performed by Brinchmann et al. (2008) comparing WR and non-WR galaxy data from SDSS observations also yields to a similar conclusion. The recent, more detailed, analysis of a sample of WR galaxies performed by López-Sánchez & Esteban (2010b) also reported high N/O ratios in...
six WR galaxies. These authors indicated that the high N/O values should dilute in a quick period because of both the decreasing of the star formation activity and the releasing of new, fresh material which is dispersed and mixed with the existing gas of the galaxy. Furthermore, the effects of the WR stars into the ISM are also diluted because of aperture effects (López-Sánchez & Esteban 2009). Only very careful analyses of such systems (e.g. López-Sánchez & Esteban 2010b) will help to solve the puzzle of the high N/O ratios sometimes found in starburst galaxies.

5.2 Use of empirical calibrations in 2D spectroscopy data

We also study the results provided by the so-called empirical calibrations of the oxygen abundance [see Kewley & Ellison (2008) and López-Sánchez & Esteban (2010b) for recent reviews] when analysing data provided by 2D optical spectroscopy, which in many occasions have a good determination of all important nebular lines involved in the most common empirical calibrations (i.e. [O iii] 3727, Hβ, [O ii] λλ4959,5007, Hα, [N ii] λλ6583). Ratios between these bright emission lines define the parameters R_21, P, y, N_2 and O_3N_2 [see definitions in appendix A of López-Sánchez & Esteban (2010b)]. Empirical calibrations are very commonly used to get a rough estimation of the metallicity of star-forming galaxies when the electron temperature of the ionized gas cannot be determined (i.e. there are no detections of the faint auroral lines).

Although some precautions must be taken into account when analysing star-forming galaxies with intermediate metallicities, 7.9 ≤ 12+log(O/H) ≤ 8.4, (Yin et al. 2007), it seems that the combination of the R_21 and an excitation parameter (P or y) have the necessary information for the determination of accurate abundances in extragalactic H II regions. The comparison between the oxygen abundances provided by empirical calibrations and those determined via the direct method performed by López-Sánchez & Esteban (2010b) concluded that the Pilyugin method (Pilyugin 2001a,b; Pilyugin & Thuan 2005) is nowadays the best suitable empirical calibration to derive the oxygen abundance of star-forming galaxies. However, the results provided by empirical calibrations based on photoionization models (McGaugh 1991; Kewley & Dopita 2002; Kobulnicky & Kewley 2004) are systematically 0.2–0.3 dex higher than those found following the direct method. This result has been later confirmed by Moustakas et al. (2010), who found differences of ~0.6 dex between both kinds of method. On the other hand, Yin et al. (2007) indicated that the N_2 and the O_3N_2 indices are useful for calibrating metallicities of galaxies with 12+log(O/H) < 8.5. López-Sánchez & Esteban (2010b) concluded that the relations between these two parameter and the oxygen abundance provided by Pettini & Pagel (2004) give acceptable results for objects with 12+log(O/H) > 8.0. Pérez-Montero & Contini (2009) established that empirical calibrations using the O_3N_2 parameter are not valid for objects with 12+log(O/H) ≤ 8.0. However, the effects of such empirical calibrations using 2D spectroscopic data have not been explored so far.

Fig. 12 shows the oxygen abundance maps of the observed star-forming region [HL90] 111 within IC 10 derived from four of the most common empirical calibrations: Pilyugin (2001a,b), which involve the R_21 and the P parameters; Kobulnicky & Kewley (2004), which is based on the photoionization models presented by Kewley & Dopita (2002) and considers the R_21 and the y parameters to iteratively derive the oxygen abundance and the ionization parameter q; the bicubic relation between the oxygen abundance and the N_2 parameter derived by Pettini & Pagel (2004); and the linear fit between the oxygen abundance and the O_3N_2 parameter also determined by Pettini & Pagel (2004). As the oxygen abundance determined using the direct method in IC 10 is found between the low-metallicity [12+log(O/H) ≤ 8.1] and the high-metallicity [12+log(O/H) ≥ 8.4] branches, we assumed the average value between the Pilyugin (2001a,b) calibrations, but always the metallicity derived for the low branch following the Kobulnicky & Kewley (2004) calibration. The four panels shown in Fig. 12 have the same scale in the oxygen abundance, between 8.0 and 8.4.

The oxygen abundance map provided by the Pilyugin (2001a,b) calibration (top-left panel in Fig. 12) shows a more or less constant value, although it clearly has lower values in the high-ionization regions [12+log(O/H) ~ 8.13] than that in the low-ionization regions [12+log(O/H) ~ 8.21], but both agree within the errors (±0.10 dex) and, although slightly lower, with the value determined using the direct method [12+log(O/H) = 8.26 ± 0.09]. If using the Pilyugin & Thuan (2005) calibration, the resulting metallicity map has a similar structure to that shown in top-left panel of Fig. 12, but the derived values are systematically ~0.05–0.10 dex lower than those determined following the Pilyugin (2001a,b) method. In any case, as we will discuss below, it is evident that there is some effect of the ionization degree on the determination of the oxygen abundance and that this calibration seems to be not suitable for looking for chemical differences smaller than ~0.10–0.15 dex using 2D spectroscopic maps.

The situation is somewhat similar when using the Kobulnicky & Kewley (2004) calibration (top-right panel in Fig. 12). As we see, this calibration provides oxygen abundances between 8.04 and 8.38, with the lower values located again in the high-ionization regions. Spaxels which have higher oxygen abundances following this method are typically located in the external areas of the star-forming regions, where the ionization degree is lower and the uncertainty in the [O iii] λ3727 flux is higher. In any case, we note that the results derived from the Kobulnicky & Kewley (2004) calibration have a higher dispersion than those obtained following the Pilyugin method, and therefore this calibration should be used with caution when analysing the chemical abundances of 2D spectroscopic maps.

The ionization structure of the giant H II regions we are observing with our PMAS data is indeed playing an important role in the determination of the oxygen abundances using empirical calibrations. That is very evident when using the N_2 and O_3N_2 parameters, which strongly depend on the ionization degree of the gas. The oxygen abundance map obtained using the Pettini & Pagel (2004) calibrations involving the N_2 (bottom-left panel in Fig. 12) and the O_3N_2 (bottom-right panel in Fig. 12) parameters directly reflect the ionization structure (see Fig. 7), having lower oxygen abundances [12+log(O/H) ~ 8.10 and 8.05, respectively] in the high-ionization region and higher oxygen abundances [12+log(O/H) ~ 8.30] in the low-ionization areas.

The correlation between the ionization degree and the results provided by the empirical calibrations are shown in Fig. 13, that plots the reddening-corrected [O iii] λ5007/[O ii] λ3727 ratio versus the oxygen abundance derived from empirical calibrations for the spaxels that possess an useful measurement of the [O iii] λ3727 emission line. From this figure, it is evident that empirical calibrations give lower oxygen abundances in regions with higher ionization degree, with a monotonic increasing of the oxygen abundance with decreasing ionization degree in all cases except for the Pilyugin & Thuan (2005) calibration (which changes this tendency for [O iii] λ5007/[O ii] λ3727 ≤ 1.0). Fig. 13 also shows that the results provided by the Kobulnicky & Kewley (2004) method have a higher dispersion than those obtained using other empirical calibrations,
and that they tend to be between 0.1 and 0.2 dex higher than the others.

However, when we integrate the individual spectra of an H II region, the result provided by the empirical calibrations are closer to those derived from the Te method. Table 3 lists all oxygen abundances determined using empirical calibrations in all the regions analysed here, including all the observed area. As we see, Pilyugin (2001a, b) calibration provides a constant value of $12 + \log(O/H) \sim 8.12$, that is $\sim 0.14$ dex lower than the oxygen abundance determined by the direct method. Pilyugin & Thuan (2005) calibration provides somewhat lower values, $12 + \log(O/H) \sim 8.10$. The Kobulnicky & Kewley (2004) method gives a relatively good value for the bright H II regions ($12 + \log(O/H) \sim 8.20$), but the values obtained for the hole and AP 4 (the two spaxels where the blue WR bump is detected) are much lower. When integrating the flux of all the H II region, the Pettini & Pagel (2004) calibrations using the $N_2$ and $O_3N_2$ indices also provide oxygen abundances that agree within the errors with those determined using the direct method.

Beside the ionization structure of the H II regions, other biases (such as the hardness of the ionizing radiation field, the structural parameters of the H II regions or the star formation history of the host galaxy) may also affect to the determination of the chemical abundances using empirical calibrations (Stasinska 2010). Hence, we conclude that the analysis of star-forming galaxies (and strong starbursting, WR galaxies in particular) using 2D spectroscopy needs observations deep enough to detect (at least in the brightest H II regions) the faint auroral lines, if a good determination of the chemical abundances and physical conditions of the ionized gas is wanted to be achieved (e.g. James et al. 2009, 2010). The deep observations will also provide a better estimation of the $[O II] \lambda 3727$ flux, which is essential to precise the total oxygen abundance. In the case this doublet cannot be observed, deep observations at $\lambda 7330$ are needed to get a good determination of the $[O II] \lambda \lambda 7318, 7330$ emission.
The age of the most recent star formation event is $\sim 3.3$ Myr.

One of our main aims is to precise the places where WR stars are located via the detection of the blue and/or red WR bumps. Only two spaxels show an unambiguous detection of the broad He $\lambda$ 4686 emission line. This feature seems to be produced by a single WNL star, its position coincides with [MAC92] 24B. We report a possible N and He enrichment at the same location where the WR feature is found. Moreover, the enrichment pattern is roughly consistent with that expected for the pollution of the ejecta of a single or a very small number of WR stars. This result suggests that the fresh material released by massive stars is quickly incorporated into the surrounding ISM. Furthermore, this chemical pollution is very localized ($\sim 2$ arcsec $\sim 7.8$ pc) and it should be difficult to detect in star-forming galaxies beyond the Local Volume.

The reddening coefficients derived from the H$\alpha$/H$\beta$ and the H$\gamma$/H$\beta$ ratios have a better agreement when the absorption underlying the H$\beta$ Balmer lines is considered. We find a correlation between the electron density of the ionized gas and the reddening coefficient, indicating that denser regions have higher extinction. Furthermore, the low reddening coefficients computed around the spaxels where the WR features are detected suggest that the gas surrounding the massive stars has been evacuated or partially destroyed. In the spaxel just to the north of the WR stars location we also detect a broad H$\alpha$ component underlying the nebular H$\alpha$ emission that may be related to a remnant of a recent SN explosion.

We discuss the use of the most common empirical calibrations to estimate the oxygen abundances of the ionized gas in nearby galaxies from 2D spectroscopic data. The ionization degree of the gas plays an important role when applying these empirical methods, as they tend to give lower oxygen abundances with increasing ionization degree. We finally stress the importance of the detection of the auroral lines to derive the electron temperature of the ionized gas and obtain a precise map of the chemical abundances in extragalactic H$\alpha$ regions.

### 6 CONCLUSIONS

In this paper, we present results from integral field spectroscopy of the intense star-forming region [HL90] 111 within the starburst galaxy IC 10. This study is based on PMAS data, which cover a wavelength range of 3500–7150 Å, with an effective spectral resolution of 3.6 Å, and map an area $16 \times 16$ arcsec$^2$ with a spatial sampling of $1 \times 1$ arcsec$^2$, that corresponds to 3.88 pc$^2$ at the distance to IC 10. We obtain maps of different emission lines and analysed the extinction, physical conditions, nature of the ionization and chemical abundances of the ionized gas, as well determined locally the age of the last star formation event.

By defining several apertures, we study the main integrated properties of some regions within [HL90] 111. For the whole FOV, we derive an extinction in the V band of $A_V = 3.05 \pm 0.11$ mag, a total mass of ionized gas of $(1.76 \pm 0.10) \times 10^5$ M$_\odot$, an SFR density of $1.64 \times 0.09$ M$_\odot$ yr$^{-1}$ kpc$^{-2}$, an oxygen abundance of $12+\log(O/H) = 8.26 \pm 0.09$ and a nitrogen to oxygen ratio of $\log(N/O) = -1.42 \pm 0.12$. The age of the most recent star formation event is $\sim 3.3$ Myr.

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Table 3. Oxygen abundances, in the form $12+\log$(O/H), of the regions analysed in IC 10 using our PMAS data determined using empirical calibrations.

| Method | Parameters | [HL90] 111 | AP1 (c) | AP2 (hole) | AP3 (d) | AP4 (WR 24) |
|--------|------------|------------|---------|------------|---------|-------------|
| Direct | $T_e$      | 8.26 $\pm$ 0.09 | 8.22 $\pm$ 0.08 | 8.22 $\pm$ 0.17 | 8.23 $\pm$ 0.09 | 8.20 $\pm$ 0.12 |
| P01    | $R_{23}$, $P$ | 8.15 | 8.12 | 8.10 | 8.13 | 8.11 |
| PT05   | $R_{23}$, $P$ | 8.13 | 8.10 | 8.03 | 8.13 | 8.07 |
| KK04   | $R_{23}$, $\gamma$ | 8.25 | 8.17 | 8.00 | 8.22 | 8.10 |
| PP04b  | $N_2$     | 8.22 | 8.13 | 8.08 | 8.18 | 8.15 |
| PP04c  | $O_3$ $N_2$ | 8.20 | 8.11 | 8.07 | 8.15 | 8.12 |
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