Mapping the ionized gas of the metal-poor HII galaxy PHL 293B with MEGARA

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ABSTRACT

Here we report the first spatially resolved spectroscopic study for the galaxy PHL 293B using the high-resolution GTC/MEGARA integral field unit (IFU). PHL 293B is a local, extremely metal-poor, high ionization galaxy. This makes PHL 293B an excellent analogue for galaxies in the early Universe. The MEGARA aperture (∼12.5” × 11.3”) covers the entire PHL 293B main body and its far-reaching ionized gas. We created and discussed maps of all relevant emission lines, line ratios and physical-chemical properties of the ionized ISM.

The narrow emission gas appears to be ionized mainly by massive stars according to the observed diagnostic line ratios, regardless of the position across the MEGARA aperture. We detected low intensity broad emission components and blueshifted absorptions in the Balmer lines (Hα, Hβ) which are located in the brightest zone of the galaxy ISM. A chemically homogeneous, across hundreds of parsecs, is observed in O/H. We take the oxygen abundance 12+log(O/H) = 7.64 ± 0.06 derived from the PHL 293B integrated spectrum as the representative metallicity for the galaxy. Our IFU data reveal for the first time that the nebular HeIIλ4686 emission from PHL 293B is spatially extended and coincident with the ionizing stellar cluster, and allow us to compute its absolute HeII ionizing photon flux. Wolf-Rayet bumps are not detected excluding therefore Wolf-Rayet stars as the main HeII excitation source. The origin of the nebular HeIIλ4686 is discussed.

Key words: HII regions — galaxies: dwarf — galaxies: individual: PHL 293B — galaxies: ISM — galaxies: starburst

1 INTRODUCTION

HII galaxies are the most metal-poor starbursts in the local Universe (e.g., Westera et al. 2004, Kehrig et al. 2004, Izotov, Thuan, & Guseva 2012, James et al. 2017). These galaxies present intense star-formation rates, and they usually have low masses and blue optical colours. The hot, luminous massive stars present in HII galaxies give off vast quantities of high-energy UV photons which ionize the gas producing strong nebular emission-line spectra (e.g., Kehrig, Telles, & Cuisinier 2004, Cairós et al. 2009, 2010).

PHL 293B is a very compact HII galaxy (effective radius of its star-forming component ~ 0.7”; e.g., Papaderos et al. 2008) which belongs to the “Palomar-Haro-Luyten” survey of faint galaxies (see French 1980, Kinman & Davidson 1981). The ionized gas of PHL 293B presents a very low oxygen abundance of 12+log(O/H) ≈ 7.6-7.7 (~ 1/10 solar metallicity).

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1 assuming a solar abundance 12+log(O/H)⊙ = 8.69 (Asplund et al. 2009)
e.g., French [1986]; Kinman & Davidson [1981]; Papaderos et al. [2008]; Izotov et al. [2011]; Fernández et al. [2018]). Moreover, PHL 293B shows ultra-high excited gas indicated by the presence of the nebular HeII λ4686 emission (e.g., French [1981]; Izotov, Thuan & Guseva [2007], and its very high specific star formation rate (sSFR = SFR/M* ∼ 6 Gyr⁻¹; see table 4 from Filho, et al. [2013] is comparable to those found in the high-redshift Universe (e.g., Stark [2016]). These features are more commonly observed and predicted in distant star-forming galaxies in comparison with local starbursts (e.g., Lehner, et al. [2013]; Mainali, et al. [2013]; Izotov, Thuan & Guseva [2019]; Sobral, et al. [2019]). This makes PHL 293B a remarkable place nearby that allows us to study in detail physical conditions which may be predominant in primeval starbursts (see also Kehrig et al. [2016]; Guseva, et al. [2017]; Izotov, et al. [2018]; Kehrig, et al. [2018]; Sanchy, et al. [2019]). The optical spectrum of PHL 293B shows the typical strong narrow emission lines normally seen in the spectra of HI galaxies. Besides, its spectrum exhibits other features as low-intensity broad wings and blueshifted narrow absorptions in the hydrogen recombination lines (e.g., Izotov & Thuan [2009]; Terlevich, et al. [2014], and references therein). Table I lists other general properties of PHL 293B. Fig. 1 shows a three-colour composite image of PHL 293B from the Hubble Space Telescope (HST)/WFC3 which reveals an extended gaseous nebulae and star-forming activity mainly present in the southern zone of the galaxy (see also Papaderos et al. [2008]).

In the last years, spatially resolved spectroscopy has opened a new window onto our understanding of the ionized gas in low-redshift SF galaxies, preventing us from an over-simplified view of it (e.g., Kehrig, et al. [2008, 2013]; Duarte Puertas, et al. [2013]; Ucci, et al. [2013]; Sánchez [2020]). In this work, we present the first 2D spectroscopic study of PHL 293B based on commissioning observations with the Multi Espectrógrafo en GTC de Alta Resolución para Astronomía (MEGARA; see next section). Our MEGARA data provide a detailed scanning of the structure and properties of the PHL 293B ionized gas. Moreover, we derive the first integrated spectrum and total HeII-ionizing photon flux from PHL 293B.

The paper is organized as follows. In Section 2, we report observations and data reduction. Flux measurements and emission line intensity maps are presented in Section 3. In Section 4 we show the 2D view of the ionization structure and nebular properties. In Section 5, we present the integrated properties from selected regions of PHL 293B. Section 6 discusses the spatially resolved HeII λ4686-emitting region and the origin of the HeII excitation. Finally, Section 7 summarizes the main conclusions derived from this work.

2 OBSERVATIONS AND DATA REDUCTION

The data of PHL 293B were obtained with MEGARA (see Gil de Paz et al. [2018]; Carrasco et al. [2018]), attached to the 10.4m GTC telescope at the Roque de los Muchachos Observatory. Observations were taken during the second commissioning run in 2017 July 25th and 29th, using the Large Compact Bundle (LCB) IFU mode which provides a field of view (FOV) of 12.5×11.3 arcsec² (~ 1.4 kpc × 1.3 kpc) at the distance of 23.1 Mpc; see Fig. 1, with a spaxel² diameter of 0.62 arcsec. In order to cover the main optical emission-lines, the observations were carried out with three gratings; we used the “blue” VPH405-LR (centered at 4025 Å) and “green” VPH480-LB (centered at 4785 Å) gratings which give spectral ranges (∆Å)/dispersions (Å pix⁻¹) of ~ 3653-4386/0.17 and ~ 4332-5196/0.20, respectively. On the red side, the VPH665-HR (centered at 6602 Å) was utilized, providing a spectral range from ~ 6445-6837 and 0.09 Å pix⁻¹. The resolving power of the gratings are ~ 6000 in case of LR VPHs and ~ 20000 for VPH665-HR.

We observed a total of 2.25 hours on the galaxy, with the integration time split into three exposures for each VPH: 3 × 600 s for VPH405-HR and VPH480-LR each, and 3 × 1500 s for VPH405-LR. The seeing was about 1 arcsec and 0.5 arcsec during the first and second observing nights, respectively. All science frames were observed at airmasses ≤ 1.2 to minimize the effects due to differential atmospheric refraction. Additionally, all necessary calibration frames (exposures of arc lamps and of continuum lamps) were obtained.

The data reduction and sky subtraction were carried out using the MEGARA Pipeline as described in Pascual et al. [2019]. Due to severe haze throughout the observing run, we did not flux-correct the science frames.

Table 1. General Properties of PHL 293B

| Parameter | PHL 293B |
|-----------|----------|
| Alternate names | Kinman Dwarf, A2228-00 |
| R.A. (J2000.0) | 22h 30m 36.s8 |
| DEC. (J2000.0) | -00° 06′ 37′′ |
| redshift | 0.0051 |
| HType⁴ | Im |
| Scale (pc/°) | 112 |
| (B-V)⁵ | 0.56 ± 0.05 |
| (V-R)⁵ | 0.27 ± 0.04 |
| Mv⁵ (mag) | -14.37 |
| Av⁴ (mag) | 0.193 |

² Individual elements of IFUs are usually named “spatial pixels” (so-called “spaxels”); the term is used to distinguish a spatial element on the IFU from a detector pixel.

⁴ Distance taken from the NASA/IPAC Extragalactic Database (NED).
⁵ Hubble Type from NED.
⁶ From Cairós et al. [2001].
⁷ Galactic extinction from Schlafly & Finkbeiner [2011].
IFS MEGARA data of the metal-poor galaxy PHL 293B

3 FLUX MEASUREMENTS AND EMISSION LINE INTENSITY MAPS

Here we measure emission line fluxes from individual spaxels based on our own IDL scripts. On top of a linear flat continuum, we fit a Gaussian profile to each emission line using the IDL based routine MPFIT (Markwardt 2009); the peak intensity, the line width $\sigma$ and the central wavelength $\lambda_c$ for each line are kept as free parameters. Note that, due to the high spectral resolution of MEGARA, we were able to resolve the [OII] doublet and, consequently, measure its individual lines at $\lambda 3726$ Å and $\lambda 3729$ Å. In the case of the H$\alpha$+[Nii] lines, we perform a simultaneous fit keeping a nitrogen [Nii]$\lambda6584$/[Nii]$\lambda6548$ line ratio of 3. Previous work, based on single-aperture/long-slit spectroscopy of the central star-forming (SF) knot of PHL 293B, have detected the presence of several components for the H$\alpha$, H$\beta$ lines (e.g., Izotov & Thuan 2009; Terlevich et al. 2014; Fernández et al. 2018). Following these authors, we fit these Balmer lines assuming three Gaussian components: narrow + broad emission, and one absorption component. Errors in the derived parameters (line flux, peak intensity, line width $\sigma$, central wavelength $\lambda_c$) are estimated by using the bootstrap method.

By combining the line fluxes with the position of the spaxels on the sky, we create all maps presented in this paper. Figure 2 exposes the intensity maps for several emission lines; only fluxes with S/N > 3 are displayed. We show for the first time the spatial distribution for the broad H$\alpha$/H$\beta$ components for PHL 293B. The global spatial structure of the brightest lines (narrow H$\beta$, [OIII]$\lambda5007$, and narrow H$\alpha$) is similar, with [OIII]$\lambda5007$ and narrow H$\alpha$ emission covering almost the entire FOV. The spatial distribution of the fainter lines (e.g., [OIII]$\lambda4363$, HeII$\lambda4686$, [Nii]$\lambda6584$, [Sii]$\lambda6717+6731$), and the broad H$\beta$ and H$\alpha$ are restricted to the inner parts of the galaxy.

When comparing the [OIII] emission distribution to that of other relatively bright lines as H$\beta$, we find the former to be more compact. This could be related partially to the fact that the [OIII] lines lie at the blue edge of the spectra (i.e. $\lambda < 3750$ Å) where we not only observe lower S/N but also expect less accuracy of the flux calibration (see Section 2 for details; see e.g., Sánchez, et al. 2012; Yan, et al. 2016; López-Sanjuan, et al. 2014). However, we highlight that the PHL 293B ionization structure which seems to be dominated by high excitation should also play an important role;

e.g., the [OIII]$\lambda5007$ emission is spatially wide-ranging as long as the [OIII]$\lambda4363$. The sensitivity function was extrapolated to allow for their relative flux calibration.

4 SPATIALLY RESOLVED PROPERTIES OF THE IONIZED GAS

4.1 Ionization Structure

Baldwin-Phillips-Terlevich (BPT) diagrams (Baldwin, Phillips, & Terlevich 1981) are a powerful tool, widely used to separate star-forming galaxies and AGN. The spatially-resolved BPT diagrams for PHL 293B are shown in Figure 5. [OIII]$\lambda5007$/H$\beta$ vs. [Nii]$\lambda6584$/H$\alpha$, [Sii]$\lambda6717+6731$/H$\alpha$. These line ratios are not corrected for extinction, but reddening effects must be minor since these ratios involve lines which are close in wavelength. Each circle plotted in Figure 5 corresponds to a line ratio obtained from a single spaxel, where the red circles show the HeII$\lambda4686$-emitting spaxels. Based on stellar population synthesis and photoionization models, Kewley et al. (2001) proposed a theoretical demarcation curve that isolates galaxies with line ratios which are due to excitation by massive stars within HII regions from those where other ionizing source is needed. An empirical curve that differentiates between AGNs and HII-like systems was later derived by Kauffmann et al. (2003); both demarcation lines are plotted in Figure 5. For all positions in PHL 293B our emission-line ratios fall in the general locus of SF objects, i.e., below and to the left of the separation lines in the two BPT diagrams. This suggests that photoionization from hot massive stars appears to be the dominant excitation mechanism within PHL 293B.

The spatial distribution for the BPT line ratios are displayed in Figure 6. While highest and lowest values of [OIII]$\lambda5007$/H$\beta$ are found at the most inner and external zones of PHL 293B respectively, a reverse trend is observed in the [Nii]$\lambda6584$/H$\alpha$ and [Sii]$\lambda6717+6731$/H$\alpha$ maps, indicating the presence of higher excited gas inward. The [OIII]$\lambda5007$/H$\beta$ map clearly shows larger values spatially coincident with the southern HII region (i.e., the bright blue knot in Figure 1) which also comprises the HeII zone (see also the HeII$\lambda4686$ map in Figure 2). Additionally, in Figure 5 we see that the HeII-emitting spaxels tend to have higher [OIII]$\lambda5007$/H$\beta$ ratio in comparison to the other spaxels. Shall we note that despite this correlation, the hard HeII-ionizing radiation ($E > 4$ Ryd) does not have to be necessarily the main responsible for the brighter [OIII] emission since the the [OIII] lines can be excited by softer energies ($E > 2.5$ Ryd) (see e.g. Thuan & Izotov 2005).
4.2 Nebular physical-chemical properties on a spaxel-by-spaxel basis

We have used the expressions from Pérez-Montero (2017) to compute the physical properties and ionic abundances of the PHL 293B ionized gaseous nebulae. These expressions are derived from the PyNEB tool (Luridiana, Morisset & Shaw 2015).

In Fig. 7 we show the maps for the [OIII]4363/λ4363 and [SII]λ6717/λ6731 line ratios which are good indicators of the average electron density ($n_e$) in a nebula (Osterbrock & Ferland 2006). For most of the spectra, the observed [OIII]/[SII] line ratios correspond to $n_e$ values $\lesssim 300$ cm$^{-3}$ ($\lesssim 100$ cm$^{-3}$), indicating a relatively low-density ionized gas in the central parts of PHL 293B.

For the [OIII]λ4363-emitting spaxels, we have computed the electron temperature $T_e$,[OIII] values from the reddening corrected [OIII]λ4363/[OIII]λ45007 line ratio. We have measured the weak
[O\textsc{iii}]4363 line above 3\sigma for 29 spaxels which extend to an area of around 9.6 arcsec$^2$ equivalent to 0.12 kpc$^2$ (see Fig. 2). The top-left panel of Fig. 2 presents the map of the $T_e$([O\textsc{iii}]) which reveals values going from $\geq$ 14,000 K to near 20,000 K, with a good fraction of the points clustering around the average $T_e$ value of ~18,300 K. The relation between $T_e$([O\textsc{iii}]) and the S/N measured for the [O\textsc{iii}]4363 line is plotted in the bottom panel of Fig. 2 where no systematic effects are observed. This is an evidence that the largest values of $T_e$([O\textsc{iii}]) that we derive are not an effect of overestimated [O\textsc{iii}]4363 flux measurements. We have used the $T_e$([O\textsc{iii}]-$T_e$([O\textsc{i}]) empirical relationship from Pilyugin et al. (2008) to determine the $T_e$([O\textsc{iii}]) values since no low-excitation auroral line (e.g., [N\textsc{ii}]5755) has been detected in any spaxel.

The O$^+$/H$^+$ and O$^{2+}$/H$^+$ ionic abundance ratios, were computed from the [O\textsc{iii}]4372,29 and [O\textsc{iii}]5007 lines, respectively using the corresponding electron temperatures. A tiny fraction of
the unseen O$^{3+}$ ion is expected to be present in high-ionizing SF regions as the ones showing HeII emission. Based on the photoionization models from Izotov et al. (2006a), the O$^{3+}$/O ratio is > 1% only in the highest-excitation HII regions whose O$^{+}$/O$^+$ is lower than 10%. We have checked that for all [OIII]$\lambda$4363-emitting spaxels (including non-HeII$\lambda$4686 and HeII$\lambda$4686 emitting spaxels), O$^{+}$/O$^+$(O$^{2+}$) is $\geq$ 10%; therefore the total O/H is assumed to be O$^+$/H$^+$ + O$^{2+}$/H$^+$. The spatial distribution of the derived 12+log(O/H) is displayed in the top-right panel of Fig. 8 with most of the spaxels (80%) showing oxygen abundance in the range of ≈ 7.5–7.6. Our results, thus, indicate that the warm gas-phase O/H in PHL 293B stands largely constant beyond hundreds of parsecs. This agrees with the absence of significant abundance gradient commonly observed in the ionized gas of HII galaxies (e.g., Kobulnicky & Skillman 1996; Izotov et al. 1999, 2004, 2006, Izotov, Chaffee & Green 2001; Izotov et al. 2008, 2013, 2016; Perez-Montero et al. 2009, 2011).

5 INTEGRATED SPECTRA ACROSS THE MEGARA FOV OF PHL 293B

Based on our IFU data we integrated individual spectra of selected galaxy regions. We created for the first time the integrated spectrum of PHL 293B by adding the flux in all the spaxels with H$\alpha$/S/N > 100 (see Section 5 for details on the integrated spectra).
spaxel) > 3; this matches an area of ~194 arcsec² (~2.4 kpc²) enclosing basically all the nebular emission across our FOV. In addition, by summing the emission from the spaxels with Hα S/N > 100 (~11.5 arcsec²), we simulate the spectrum of the brightest region of the galaxy (hereafter Hα-HSN region⁴, and whose boundary is shown overplotted on the map of Hα (see Fig. 2). Finally, we obtained the spectrum of the region that we name PHL 293B-HeII. To do so we have integrated all HeII-emitting spaxels which covers ~3.5 arcsec² (see the HeII map in Fig. 2).

The 1D spectra mentioned above are presented in Fig. 2. We derive the fluxes of the emission-lines and associated uncertainties for these spectra using the same method as for individual spaxels (see Section 3). We computed the logarithmic reddening coefficient, C(Hβ), by performing a least square fit to the ratio of the measured-to-theoretical Balmer decrements as a function of the Miller & Mathews (1972) galactic reddening law (see also Hägele et al. 2008). The uncertainty of the fit is adopted as the error in C(Hβ). The narrow component of the four strongest Balmer emission lines (Hα, Hβ, Hγ, Hδ) have been used. Intrinsic Balmer line ratios were taken from Osterbrock & Ferland (2006) assuming case B recombination with electron temperature T_e=2×10⁴ K: (Hβ/Hδ)_caseB=0.26, (Hγ/Hβ)_caseB=0.47, (Hδ/Hβ)_caseB=2.75. Some issues were found concerning the C(Hβ) computation. The blue grating covers the Hδ and Hγ, and the green spectra include both Hγ and Hβ, while Hα is measured in the red grating (see Section 2). We match the blue and green spectra by using the Hγ line as reference which is measurable in both. We could not connect the green and red spectra since they share no lines. Thus, to minimize errors in the de-reddened ratios between a certain emission line and Hβ, we always take first its ratio in relation to the closest hydrogen line as referred to in Table 2; see Section 3.4. We renormalize it using the corresponding theoretical Balmer ratio.

Table 2 presents the relative fluxes of the de-reddened narrow emission lines measured from the integrated spectra; fluxes are normalized to the Hβ flux = 1000. We note that the values of C(Hβ) obtained here are in agreement with values derived for PHL 293B in the past (e.g., Izotov, Thuan, & Guseva 2013; Terlevich et al. 2011).

Figures 4 and 5 show the flux in units of 10⁻¹⁸ erg s⁻¹ cm⁻² Å⁻¹, and log [OIII]λ5007/Hβ for PHL 293B. Open circles mark the individual spaxels from the data cube; red circles show the individual HeII-emitting spaxels. The solid line (in the two panels) indicates the theoretical demarcation limit from Kewley et al. (2001) that separates objects where the gas ionization is mainly due to hot massive stars (below and to the left of the curve) from those where other ionizing mechanism is required. The dashed line in the [Nii]λ6584/Hα plot (top panel) depicts the boundary between SF systems and AGNs from Kauffmann et al. (2003). Error bars in the y-axis are the same size or smaller than the symbols, and are not plotted for the sake of clarity.
Figure 6. Maps of line ratios in logarithmic scale. East is left and North is up. The plus (+) sign is as indicated in Fig. 2.

Figure 7. Indicators of nebula electron density. Maps for $[\text{O} \text{II}] \lambda 3729/\lambda 3726$ and $[\text{S} \text{II}] \lambda 6716/\lambda 6731$. East is left and North is up. The plus (+) sign is as indicated in Fig. 2.
Also, the listed Hα/Hβ and Hβ/Hγ ratios acceptably match their theoretical recombination values; the Hγ/Hβ ratio shown in Table 2 makes use of the green-Hγ flux, and is about 10%-15% smaller than the theoretical one. We verify that using the blue-Hγ flux instead, the ratio between the de-reddened and theoretical Hγ/Hβ lowers down to 3%-5%. The line ratios uncertainties consider error flux measurements and the error in C(Hγ), but do not take systematic uncertainties, e.g., due to the blue-green match. We note that the effects of these uncertainties on the line ratios upon which oxygen abundance and T_e[OIII] estimates are based should be marginal since we obtain values in accord with other authors (see below). Since the [OIII] lines are the most affected by extinction in our spectra, as a further check, we also corrected for reddening [OIII]λλ3726,3729/Hβ using only the green-Hγ-to-Hβ ratio. We found that the variations in [OIII]λ3726,3729/Hβ are within the quoted uncertainties in Table 2.

For our three selected galaxy regions (PHL 293B integrated, PHL 293B-HeII, Hα-HSN), we calculated physical properties and oxygen abundances as explained in Section 4 for single spaxel spectra. We calculated the nitrogen ionic abundance ratio, N%/H%, from the PYNEB-based expression from Pérez-Montero (2014), using the [NII]λ6584 emission line and assuming Te[NII] = Te[OIII]; we derived the N/O ratio under the premise that N/O= N%/O%, based on the simultude of the ionization potentials of the ions N+ and O+.

Table 2 also lists the values of C(Hβ) and physical-chemical properties obtained for each spectrum region. By looking at Table 2 and Fig. 8, we find that the measurements of the integrated line-ratios [OIII]λλ4959/4363, [NII]λλ6584/Hα, [SII]λλ6717,6731/Hα for the three selected regions are located below the demarcation lines in the BPT diagrams which implies an HII region-like ionization.

The comparison among the integrated electron temperature values from Table 2 shows similar T_e[OIII], considering the uncertainties. Concerning the oxygen abundances, we also find that the spectra of the regions PHL 293B-HeII, Hα-HSN, and PHL 293B-integrated yield equivalent values within the corresponding error bars. This is telling us that the metallicity obtained from the PHL 293B-integrated spectrum matches the O/H from the other two (physically smaller) selected zones. Therefore, according to our MEGARA data, the gas metallicity of PHL 293B is not only spatially homogenous (see previous section), but also independent of the aperture applied. Here, we take the O/H abundance of the integrated-spectrum [12+log(O/H)] of PHL 293B as the representative metallicity of PHL 293B. This value is consistent, within the errors, with those reported in previous work (e.g., Kinman & Davidson 1981; Izotov et al. 2007; Guseva et al. 2008).

Regarding the nitrogen abundance, we find that the Hα-HSN and PHL 293B-HeII regions present similar N/O ratios within the uncertainties (see Table 2). The N/O values derived here are in agreement with the typical value of Log(N/O) ≈ -1.5 to -1.6 characteristic for the plateau in the 12+log(O/H) vs. Log(N/O) relation observed for low-metallicity systems (e.g., Garnett 1994; Izotov & Thuan 1999; van Zee & Haynes 2000; Mollá et al. 2000; Pérez-Montero et al. 2011). Moreover, we confirm that the N/O ratios for these two regions...
gions match those obtained in earlier studies of PHL 293B (e.g., French 1980; Izotov, Thuan & Guseva 2007).

In Table 5 we list the observed fluxes and dispersion of the broad and narrow emission components of Hα and Hβ lines for the three integrated spectra described in this section. The origin of the broad emission and P Cygni-like features in the Balmer lines seen in the spectra of PHL 293B has been debated for many years. Discrepant scenarios involving a luminous blue variable star eruption, an expanding supershell or a stationary wind driven by a young cluster wind, and strongly-radiative stationary cluster wind have been proposed (e.g., Izotov, Thuan & Guseva 2007; Terlevich et al. 2014). Burke, et al. (2020) review the previous interpretations for the nature of PHL 293B including new 2019 Gemini data, and find a recent fading of broad Hα emission (see also Allan et al. 2020); a broad to narrow Hα flux ratio (Hα B/N) of 0.41 from 2001 SDSS data and 0.10 from 2019 Gemini data are reported by Burke, et al. (2020). Here we find Hα B/N ~ 0.10 for all the three integrated regions indicating that the dissipation of the broad Hα emission might have begun in 2017 when our observations were performed (see Table 5). However, while our data reveal P Cygni-like features in Hα and Hβ (see Figs. 3 and 4), P Cygni profile in Hα is not visible in the 2019 Gemini spectra according to Burke, et al. (2020). A long-lived Type IIn supernova (SN IIn) is proposed to be the most likely explanation for the optical and spectral variability of PHL 293B by Burke, et al. (2020). However, the lack of X-rays (~3 × 10^{38} erg s^{-1}; e.g., Prestwich, et al. 2013; Terlevich et al. 2014) in PHL 293B remains the big challenge to the SN IIn scenario. Larger timescales spectroscopic follow-up should be necessary to clarify the variable spectral features of PHL 293B, but this is outside the scope of our study.

6 THE NEBULAR HEII:4686 IN PHL 293B

Photons with energy beyond 54 eV are needed to ionize He twice, so HeII-emitting objects should host a relatively hard radiation field. While nebular HeII emitters are atypical of nearby galaxies, they are expected to be usual at high-z (z ≥ 6) due to the predicted harder UV-ionizing spectra at the lower metallicities typical in the far-away Universe (e.g., Smith, et al. 2015; Stark 2018; Stanway & Eldridge 2019). Next generation telescopes (e.g., JWST, ELT) are expected to detect the rest-frame UV of thousands of high-ionizing galaxies in the reionization era. Therefore, studying the HeII-ionization in metal-poor local objects is crucial to illuminate the properties of these reionization-epoch systems.

It is to be noted that the fraction of HeII-emitting systems among metal-poor objects tend to be larger than for higher metallicity galaxies observed in the local Universe (e.g., Kehrig, et al. 2011; Shirazi & Brinchmann 2012). Ultra luminous X-ray binaries (ULXB), hot massive stars and shocks are among the leading candidate sources discussed in the literature to explain the nebular HeII excitation in nearby SF galaxies (e.g., Garnett, et al. 1991; Kehrig, et al. 2011; Shirazi & Brinchmann 2012; Szécsi, et al. 2015; Sancha, et al. 2020). However, despite observational and theoretical efforts, the origin of the HeII ionization is far to be a settled matter in several cases (e.g., Garnett, et al. 1991; Kehrig, et al. 2015; Kehrig, et al. 2018; Piat, et al. 2015; Kubatova, et al. 2019; Zackrisson & Vikaeus 2020). Current stellar models keep failing to reproduce the total emergent flux beyond 54 eV, specially in metal-poor-galaxies (e.g., Kehrig, et al. 2015; Kehrig, et al. 2018; Stanway & Eldridge 2019).

The existence of narrow HeII:4686 emission in PHL 293B has been noted before from long-slit spectroscopy (e.g., Izotov, Thuan & Guseva 2007; Papaderos, et al. 2008; Guseva, et al. 2009; Izotov, et al. 2011). Here, we produce the first HeII:4686 spectral map of PHL 293B using MEGARA (see Fig. 2). From our data, we checked that the FWHM of the HeII:4686 line matches that of other nebular emission lines like the strong [OIII] λ5007. The measured values of the mean and standard deviation for the FWHM(HeII)/FWHM([OIII]) ratio are ~ 1.10 and 0.10, respectively. The narrow line profile for the HeII:4686 emission and its spatial extent are evidence of its nebular origin (see also Shirazi & Brinchmann 2012).

PHL 293B was observed with the Chandra X-ray Observatory on 2009 September for a total exposure time of 7.7 ks using the ACIS-S3 detector. There is no detection of X-ray emission up to an upper limit of ~ 3 × 10^{38} erg s^{-1} (Prestwich, et al. 2013; Terlevich, et al. 2014). This indicates that X-ray sources are unlikely to be the main responsible for the HeII ionization in PHL 293B. On the other hand, the BPT line-ratios measured both from the single HeII-emitting spaxels and integrated spectra show values typical of HII region-like ionization (see Fig. 5 and Table 5), indicating hot massive stars as the dominant excitation source. This agrees with Burke, et al. (2020) who claim that the narrow emission gas in PHL 293B is likely the HII region ionized primarily by stellar emission. Wolf-Rayet (WR) emission bumps are not detected in the spectra of PHL 293B. This means that different types of hot stars other than WRs should be contributing to the HeII excitation. This result agrees with the studies of the HeII-emitting extremely metal-poor (XMP) galaxies IZw18 and SBS 0335-052E (see Kehrig, et al. 2013; Kehrig, et al. 2018). A detailed comparison of our observations to model predictions would be needed to constrain the hot ionizing stellar population in PHL 293B, but this exercise is beyond the scope of this paper.

For the PHL 293B-HeII spectrum (obtained by adding all the HeII-emitting spaxels; see Fig. 2 and Section 5), we computed the HeII ionizing photon flux, Q(HeII)|_{PHL 293B-HeII} = 3.66 × 10^{49} photons s^{-1} (see Table 3), from the corresponding reddening-corrected luminosity L(HeII) using the relation Q(HeII) = L(HeII)/([j(A386)];_{HeII}) (assuming case B recombination, and T_{e}([OIII]) = 2 × 10^{4} K; Osterbrock & Ferland 2006). Applying the same method for the Hα-HeII region, whose area includes the PHL 293B-HeII region (see Fig. 2 and Section 5 for details) we find that the Hα-HeII region produces Q(HeII) = 4.16 × 10^{49} photon s^{-1} (see Table 2). This is ~ 14 % higher than Q(HeII)|_{PHL 293B-HeII}, which indicates that some small fraction of gas beyond the PHL 293B-HeII region is also emitting HeII-ionizing photons. The PHL 293B-HeII and Hα-HeII regions, together produce a total Q(HeII) = 7.82 × 10^{49} photons s^{-1} which can be taken as the HeII ionizing budget measured for PHL 293B. It is worth noticing that the PHL 293B-integrated spectrum, created by summing almost all the emission across the MEGARA FOV, does not show the HeII line (see Table 4). In this regard one should bear in mind that searches for reionization-era HeII-emitters, for which only the total integrated spectra will be available, might be biased in the sense shown here, i.e., that a non-detection of the HeII line does not necessarily mean the intrinsic absence of HeII emission.

Using integral field spectroscopy (IFS), we also studied the spatial distribution of the nebular HeII emission for the XMPs SBS 0335-052E and IZw18 (Kehrig et al. 2015; Kehrig, et al. 2018). When comparing the observed Q(HeII) for different regions

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5 Gemini spectra from Burke, et al. (2020) cover from 5500 - 7500 Å.
**IFS MEGARA data of the metal-poor galaxy PHL 293B**

**Table 2.** De-reddened narrow emission line-fluxes relative to Hβ=1000 and physical properties from three selected regions

| Wavelength (Å) | PHL 293B-Integrated<sup>b</sup> | Hα-HSN<sup>c</sup> | PHL 293B-HeII<sup>d</sup> |
|---------------|---------------------------------|-----------------|--------------------------|
| 3726 [O II]   | 585 ± 168                       | 464 ± 46        | 296 ± 32                 |
| 3729 [O II]   | 760 ± 118                       | 544 ± 42        | 340 ± 27                 |
| 3868 [NeIII]  | 417 ± 30                        | 418 ± 7         | 407 ± 6                  |
| 4100 Hα       | 286 ± 16                        | 277 ± 5         | 271 ± 4                  |
| 4340 Hγ       | 390 ± 18                        | 417 ± 10        | 412 ± 9                  |
| 4363 [O III]  | 84 ± 14                         | 106 ± 6         | 113 ± 5                  |
| 4686 He II    |                                | 20 ± 2          | 26 ± 2                   |
| 4714 [Ar IV]  |                                | 21 ± 2          | 24 ± 3                   |
| 4740 [Ar IV]  |                                | 14 ± 2          | 16 ± 2                   |
| 5007 [O III]  | 3568 ± 38                       | 4068 ± 44       | 4406 ± 32                |
| 6563 Hα (Narrow) | 2717 ± 55                      | 2831 ± 39       | 2804 ± 28                |
| 6584 [N II]   |                                | 20 ± 3          | 16 ± 4                   |
| 6678 HeI      |                                | 24 ± 1          | 23 ± 1                   |
| 6717 [S II]   | 82 ± 10                         | 54 ± 2          | 36 ± 1                   |
| 6731 [S II]   |                                | 36 ± 2          | 27 ± 2                   |
| c(Hβ)         | 0.11 ± 0.02                     | 0.14 ± 0.01     | 0.30 ± 0.01              |
| F(HeII) (erg s<sup>-1</sup> cm<sup>-2</sup>) | 4.28×10<sup>-14</sup> | 2.74×10<sup>-14</sup> | 1.86×10<sup>-14</sup> |
| F(Hα) (erg s<sup>-1</sup> cm<sup>-2</sup>) |       | 5.41×10<sup>-16</sup> | 4.76×10<sup>-16</sup> |
| L(HeII)/(erg s<sup>-1</sup>)<sup>e</sup> |       | 3.45×10<sup>37</sup> | 3.04×10<sup>37</sup> |
| Q(HeII)(photos s<sup>-1</sup>)<sup>f</sup> |       | 4.16×10<sup>49</sup> | 3.66×10<sup>49</sup> |
| log ([N II]6584/Hα) |       | -2.16 | -2.25 |
| log ([S II]6717+6731/Hα) |       | -1.50 | -1.66 |
| log ([O III]5007/Hβ) |       | 0.55 | 0.61 |
| T<sub>e</sub>([O III]) (K) | 16,335 ± 1500 | 17,243 ± 548 | 17,089 ± 450 |
| T<sub>e</sub>([O II])<sup>g</sup> (K) | 14,361 ± 1080 | 15,015 ± 394 | 14,904 ± 324 |
| 12+log(O<sup>+</sup>/H<sup>+</sup>) | 7.08 ± 0.11 | 6.90 ± 0.04 | 6.71 ± 0.04 |
| 12+log(O<sup>+++</sup>/H<sup>++</sup>) | 7.50 ± 0.07 | 7.51 ± 0.02 | 7.55 ± 0.02 |
| 12+log(O/H)<sup>h</sup> | 7.64 ± 0.06 | 7.60 ± 0.02 | 7.61 ± 0.02 |
| 12+log(N<sup>+</sup>/H<sup>+</sup>) |       | 5.21 ± 0.07 | 5.12 ± 0.11 |
| log(N/O) |       | -1.68 ± 0.08 | -1.59 ± 0.11 |

(a) In all cases, the reddening correction for each line flux was performed relative to the closest Balmer recombination line (see text for details)
(b) PHL 293B-integrated spectrum obtained by co-adding all spaxels with Hα S/N > 3
(c) Spectrum created by adding all spaxels with Hα S/N > 100
(d) Spectrum obtained by summing all HeII-emitting spaxels
(e) HeII luminosity at the distance of 23.1 Mpc
(f) Number of ionizing photons shortward of the He<sup>+</sup> edge (see the text for details)
(g) T<sub>e</sub>([O II]) = 0.72× T<sub>e</sub>([O III])<sup>+</sup> [Pilippin et al. 2004]
(h) Q/H = O<sup>+</sup>/H<sup>+</sup> + O<sup>+++</sup>/H<sup>++</sup>

**Table 3.** Fit parameters of the broad and narrow hydrogen (Hβ, Hα) emission lines for the regions listed in Table 2

| Region<sup>a</sup> | Property | Hβ Narrow | Hβ Broad | Hα Narrow | Hα Broad |
|-------------------|----------|-----------|----------|-----------|----------|
| PHL 293B-Integrated | $\sigma$<sub>obs</sub> (Å)<sup>c</sup> | 0.50 | 0.46 | 2.3 |
|                   | $\sigma$<sub>obs</sub> (Km/s)<sup>d</sup> | 31 | 21 | 105 |
| Ho-HSN            | $\sigma$<sub>obs</sub> (Å)<sup>c</sup> | 0.49 | 2.22 | 0.46 | 3.17 |
|                   | $\sigma$<sub>obs</sub> (Km/s)<sup>d</sup> | 30 | 137 | 21 | 145 |
| PHL 293B-HeII     | $\sigma$<sub>obs</sub> (Å)<sup>c</sup> | 0.50 | 2 | 0.46 | 5.8 |
|                   | $\sigma$<sub>obs</sub> (Km/s)<sup>d</sup> | 31 | 123 | 21 | 174 |

(a) Regions as defined in Table 2
(b) Observed fluxes in units of 10<sup>-17</sup> erg s<sup>-1</sup> cm<sup>-2</sup>
(c) and (d) Observed $\sigma$ (= FWHM/2.35) in units of Angstrom and Km/s, respectively
across SBS 0335-052E and IZw18, we find, for both objects, that the highest absolute HeII flux and maximum Q(HeII) values correspond to the integrated spectrum of the galaxy, contrary to what we see in PHL 293B. This could suggest that the fraction of HeII-ionizing hot stars, with respect to the total massive stellar content, should be higher in SBS 0335-052E and IZw18 in comparison to the that of PHL 293B, and that a higher amount of He⁺-ionizing photons is reaching larger distances from the central star clusters in both SBS 0335-052E and IZw18. This might be related to the fact that, although the three objects are very low-Z, the specific star formation rate (sSFR) of SBS 0335-052E and IZw18 (170 Gyr⁻¹ and 166 Gyr⁻¹, respectively; Schneider, Hunt & Valiante 2016) is > 20 times that of PHL 293B sSFR ∼ 6 Gyr⁻¹ (Filho, et al. 2013). Of course, higher statistics is necessary to make stronger statements on which properties can be dominant factors to determine the HeII emitting nature of a galaxy.

All the results described above testify the importance of IFS
for this kind of analysis, which allows us to collect all HeII emission, and therefore deriving the absolute HeII ionization budget.

7 SUMMARY AND CONCLUSIONS

We have analysed MEGARA observations of the nearby, very metal-deficient galaxy PHL 293B. This kind of objects constitute excellent laboratories for probing the conditions of galaxies in the early universe. The data cover the optical wavelength range (~3700-6800 Å) within a field-of-view of ~12.5 × 11.3 arcsec². MEGARA-IFU scans the entire spatial extent of the PHL 293B main body providing us with a new 2D view of the ionized ISM in this galaxy. Maps for the spatial distribution of relevant emission lines, line-ratios and physical-chemical properties for the ionized gas have been discussed. We were able to detect low intensity broad components and P Cygni-like profiles in the Balmer lines in agreement with previous work. We have checked that such components coincide spatially with the brightest star-forming cluster of the galaxy.

The BPT-line ratios ([OIII]λ5007/Hβ, [Nii]λ6584/Hα, [Sii]λλ6717,6731/Hα) measured both from individual spaxels and integrated spectrum regions agree with HII-like ionization. We measured the [OIII]λ4363 line flux over the central parts of the galaxy covering an area of ~0.12 kpc². For this zone, we measured O/H directly from the derived electron temperature T_e[OIII], and we find no significant variations in oxygen abundance; most of spaxels have 12+log(O/H) values spanning around ~7.5–7.6. For the first time, we derive the PHL 293B integrated spectrum by summing the spaxels with Hα S/N > 3. We take the O/H abundance of the PHL 293B integrated spectrum, 12+log(O/H)=7.64 ± 0.06 ~ 8% solar metallicity, as the representative metallicity of the galaxy. Such value concurs with the ones on a spaxel-by-spaxel basis, and it also matches with those found in the literature.

Here, we derive the first spectral map for the nebular HeIIλ4686 line and compute the HeII ionization budget in PHL 293B. Our observations together with data from the literature indicate that neither Wolf-Rayet stars nor X-ray binaries are the main responsible for the HeII ionization in PHL 293B. This is in the line of our studies on the two XMPs SBS 0335-052E and IZw18 based on IFS. Additional IFS studies of large samples of very metal-deficient and nebular HeII-emitters are needed to better understand the nature of these objects.

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DATA AVAILABILITY

The data underlying this article are part of the MEGARA commissioning observations and are available in the article.

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