Unveiling the formation of NGC 2915 with MUSE:
A counter-rotating stellar disk embedded in a disordered gaseous environment*

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ABSTRACT

NGC 2915 is a unique nearby galaxy that is classified as an isolated blue compact dwarf based on its optical appearance but has an extremely extended H\textsc{i} gas disk with prominent Sd-type spiral arms. To unveil the starburst-triggering mystery of NGC 2915, we performed a comprehensive analysis of deep VLT/MUSE integral field spectroscopic observations that cover the star-forming region in the central kiloparsec of the galaxy. We find that episodes of bursty star formation have recurred in different locations throughout the central region, and the most recent one peaked around 50 Myr ago. The bursty star formation has significantly disturbed the kinematics of the ionized gas but not the neutral atomic gas, which implies that the two gas phases are largely spatially decoupled along the line of sight. No evidence for an active galactic nucleus is found based on the classical line-ratio diagnostic diagrams. The ionized gas metallicities have a positive radial gradient, which confirms the previous study based on several individual H\textsc{i} regions and may be attributed to both the stellar feedback-driven outflows and metal-poor gas inflow. Evidence for metal-poor gas infall or inflow includes discoveries of high-speed collisions between gas clouds of different metallicities, localized gas metallicity drops and unusually small metallicity differences between gas and stars. The central stellar disk appears to be counter-rotating with respect to the extended H\textsc{i} disk, implying that the recent episodes of bursty star formation have been sustained by externally accreted gas.

Key words. Galaxies: individual: NGC 2915 – Galaxies: dwarf – Galaxies: blue compact dwarf – Galaxies: kinematics and dynamics – Galaxies: star clusters

1. Introduction

Blue compact dwarfs (BCDs) are dwarf galaxies with compact optical appearance and H\textsc{i}-region-like spectra due to highly concentrated starburst activity (e.g., Thuan & Martin 1981; Hunter & Elmegreen 2004, 2006). They are generally metal-poor (e.g., Kunth et al. 1988; Izotov & Thuan 1999), and rich in gas which has a much more extended distribution than stars (e.g., Brinks & Klein 1988; Taylor et al. 1996; Putman et al. 1998; Pustilnik et al. 2001). Such properties once led people to think that BCDs could be young systems that are experiencing their first episodes of star formation activity. However, later studies revealed the existence of ancient stellar populations in almost all of the known BCDs (e.g., Loose & Thuan 1986; Kunth et al. 1988; Papaderos et al. 1996; Cairós et al. 2001; Cairós & González-Pérez 2017a,b). Several scenarios have been put forward to understand the formation mechanisms of BCDs, including merger (e.g., Bekki 2008; Lelli et al. 2012; Zhang et al. 2020a,b), violent disk instabilities (e.g., Elmegreen et al. 2012), and cosmic web gas inflow (e.g., López-Sánchez et al. 2012; Verbeke et al. 2014), etc., but it is unclear which mechanism is the most relevant one.

NGC 2915 is an extreme case of a BCD in the local Universe, which is also known as one of the closest BCDs ($M_B = -15.9$ mag; $D = 4.1$ Mpc; Meurer et al. 2003), making it an ideal laboratory for understanding the evolution of this kind of galaxies. The H\textsc{i} gas content of this galaxy is very high ($M_{\text{HI}}/L_B \sim 1.7 M_\odot/L_\odot$; $M_{\text{HI}} \sim 4.5 \times 10^8 M_\odot$; Elson et al. 2010), and extremely extended in distribution ($\sim 6 R_{25}$; Becker et al. 1988), showing well-defined spiral structures that are not seen in optical images (Meurer et al. 1996). In the central region, there are two H\textsc{i} gas clumps similar in mass and size (Elson et al. 2010), which were mistaken for a bar structure in low-resolution H\textsc{i} maps (Meurer et al. 1996) for a long time. The H\textsc{i} velocity field shows the regular rotation, and its rotation curve becomes flat at large radii (Becker et al. 1988; Meurer et al. 1996; Elson et al. 2010). Its dark matter content is extremely high ($M_{\text{DM}}/L_B \sim 140 M_\odot/L_\odot$, Elson et al. 2010) and dominant at all radii. Also, the dark matter halo has a dense and compact core (Bureau et al. 1999), resulting in a very deep potential well in...
the center. Signs of a warp in the H\textsc{i} disk are found (Meurer et al. 1996), indicating possible environmental interaction with a partner. A low-surface-brightness galaxy named SGC 0938.1-7623 (Corwin et al. 1985; Karachentseva & Karachentsev 1998), ~42° away from NGC 2915 (or projection distance is about 50 kpc by assuming the distance of NGC 2915), is the only candidate neighbor, without confirmation by either radial velocity or distance.

According to a study of multi-wavelength images of NGC 2915 by Meurer et al. (1994), almost all the young stellar populations and H\textsc{ii} regions are located near the center of the galaxy. Werk et al. (2010) studied five H\textsc{ii} regions within the 1.2 × Holmberg radius and found a non-negative radial gradient of gas-phase metallicity. The apparent under-abundant inner disk and overabundant outer disk in metallicities indicate that there may be certain mixing mechanisms redistributing the heavy elements produced by star formation. In addition, Sersic & Donzelli (1992) and Meurer et al. (1994) found that the optical surface brightness profiles of NGC 2915 are well described by an up-bending double-exponential form, with a sharp turning at a radius of ~30 arcsec. The inner exponential disk, the so-called BCD part, mainly consists of the blue and young stellar population, whereas the outer exponential is red and old, similar to a dE galaxy. Meurer et al. (2003) discovered three metal-poor globular clusters based on HST images that cover a small portion of the outer disk, implying an abnormally high specific frequency of globular clusters for the whole system. Although being extremely rich in gas, star formation activity is barely detected in the extended outer H\textsc{i} disk. The rotational shear may play a role in inhibiting the star formation there (Meurer et al. 1996; Elson et al. 2012).

The triggering mechanism of the highly concentrated star formation in NGC 2915 is still unclear. In this study, taking advantage of the high-quality integral field spectroscopy from MUSE (Bacon et al. 2010) on the Very Large Telescope (VLT), we present a study of the stellar population distributions and kinematics of NGC 2915, in an effort to shed light on the formation and evolution of this galaxy. The rest of this paper is structured as follows. Section 2 describes the method used in our data processing and analysis. The main results and discussion are given in Section 3. A summary follows in Section 4.

2. Observations and data reduction

2.1. MUSE data

MUSE (Bacon et al. 2010) is an integral-field spectrograph installed on the VLT of the European Southern Observatory at Cerro Paranal, Chile. The observations of NGC 2915 were taken in the wide-field mode (WFM) of MUSE, which covers a field of view (FoV) of 1′ × 1′, and has a spatial sampling of 0.2′′ × 0.2′′, a spectral resolution of ~2.5 Å (at 7000 Å), and a spectral sampling of 1.25 Å across the wavelength range from 4750 to 9350 Å.

The MUSE observations of NGC 2915 (Figure 1) were acquired over four nights in February 2015 (Program ID: 094.B-0745(A)) for a total exposure time of 12480 (13 × 960) seconds on target, without separate sky exposures. The observations cover the central 1.2×1.2 kpc of NGC 2915. We downloaded the raw science data and calibration data from the ESO Science Archive. The data were reduced with the MUSE data reduction pipeline (v2.8.3, Weilbacher et al. 2020) packaged in the ESO recipe execution tool (EsoRex, v3.13.3). We followed the standard procedure for calibration and reduction except for the sky
subtraction. For observations without separate sky exposures, the default strategy adopted by the pipeline is to select the dimmest part of the white-light image (obtained by collapsing the data cube in the wavelength dimension) for sky background estimation. We adopt a more conservative (or stricter) strategy for background selection. In particular, we first select the faintest 10% pixels in continuum and the faintest 10% pixels in [O iii]λ5007 emission, and then the common pixels from the two selections (~ 2.5% of the FoV) are used for background estimation. Finally, we refine the sky subtraction by applying the Zurich Atmosphere Purge (ZAP, Soto et al. 2016) principal component analysis algorithm. We note that the seeing conditions vary from exposure to exposure (1.16′′ – 2.00′′), and the final combined data cube has a full width at half maximum (FWHM) of the point spread function (PSF) of 1.54′′, with little dependence on wavelength.

2.2. HST images

There exist multi-band archival HST/WFPC2 (Wide Field and Planetary Camera 2) images of NGC 2915, including the U (F336W), B (F439W), V (F555W), and I (F814W)-band images that were taken with exposure times of 4400, 2100, 600 and 600 seconds respectively (Program ID: 11987). The fully processed images of NGC 2915 are retrieved from the Hubble Legacy Archive, and are used in the current study for the following two purposes. First, to select a clean sample of star clusters from the relatively low-spatial-resolution MUSE data, we use the HST images to help remove contaminations from single stars (either foreground or within NGC 2915). Second, to have a better wavelength coverage for reliable stellar population modeling, the U and B band photometry are used jointly with the MUSE spectra for full-spectrum fitting (see Section 3.1). For the second purpose, we degrade the HST images to match the spatial resolution of MUSE data, using a Gaussian convolution kernel.

3. Data analysis

3.1. 2D spectrophotometric fitting

To prepare for resolved spectral fitting, we first rebin the MUSE datacube to have a 0.6′′ × 0.6′′ spaxel size. Then, all the spaxels that have S/N < 3 near 5500 Å or are contaminated by foreground stars or background galaxies are masked out. Finally, we use the Voronoi tessellation method (Vorbin, Cappellari & Copin 2003) to adaptively rebin the spaxels to a minimum S/N of 50/Å (near 5500Å). The resultant spaxels with S/N < 50/Å are excluded from subsequent analysis. The same Voronoi binning mask is applied to the HST U, B, and V band images for a joint fit of spectroscopy and photometry.

We use the Penalized Pixel Fitting (pPXF, Cappellari & Emsellem 2004; Cappellari 2017) software to perform a simultaneous spectral fit with stellar population models and Gaussian emission line templates to each adaptively rebinned spaxel. For the stellar population models, we use single stellar population (SSP) models generated from the Flexible Stellar Population Synthesis (FSPS, Conroy et al. 2009) code. These SSP models are built with the MILES stellar library, Padova+07 isochrones and the Kroupa initial mass function (Kroupa 2001). We also include nebular continuum emission in our models. However, we note that whether or not the nebular continuum is included makes no significant difference to our results. Our SSP models cover 42 different ages ranging from 0.001 Gyr to 12.6 Gyr and 10 different metallicities from [M/H] = −1.98 to −0.20. The model spectra are smoothed to match the spectral resolution of MUSE data.

By largely following the common practice of using pPXF in the literature (e.g., Kacharov et al. 2018), we developed the following procedure to perform a joint fit of the MUSE spectra and UB broadband photometry, in order to obtain the stellar and gaseous velocity field, velocity dispersion, emission-line flux and star formation histories.

**Step 1.** We obtain the stellar radial velocity and velocity dispersion of each spaxel by performing a pPXF fitting without regularization. Emission lines are masked out at this point. In order to minimize effects such as template mismatch, imperfect sky subtraction, flux calibration and wavelength-dependent reddening, a combination of tenth-degree additive and multiplicative Legendre polynomials is used in the fitting. In the next steps, the stellar velocity and velocity dispersion are fixed to the values determined here.

**Step 2.** A pPXF fitting without regularization is performed again for each spaxel, using multiplicative tenth-degree Legendre polynomials only. As in step 1, emission lines are masked out at this point. We then use the Calzetti et al. (2000) reddening law to fit the multiplicative polynomials in order to determine the wavelength-dependent reddening. After dividing the multiplicative Legendre polynomials by the wavelength-dependent reddening, we obtain a residual continuum shape correction curve for each spaxel. These correction curves are median averaged over all spaxels to form a “master” correction curve, which is applied to all spaxels. We note that the typical correction factor is about 1%

**Step 3.** The wavelength-dependent reddening curve determined above (and extrapolated to shorter wavelengths with the Calzetti law) for each spaxel is used to de-redden the corrected MUSE spectra and HST broadband photometry.

**Step 4.** Before performing a joint fit to the HST broadband photometry and MUSE spectra, we need to correct for the flux calibration difference (if any) between the two datasets. The HST V band overlaps fully with the MUSE wavelength coverage. We therefore use the V band to determine the overall flux calibration difference between HST photometry and MUSE spectra, and correct the HST U and B band photometry for this difference (≤ 0.05 mag). We then rescale the full spectra+UB noise array such that the corresponding pPXF fitting (without regularization) gives a minimum $\chi^2$/DOF = 1. Then, the Gaussian emission line templates are included in the fitting, and the relevant emission line parameters (i.e. flux, equivalent widths, velocity, and velocity dispersion) are measured.

**Step 5.** With all of the above corrections applied to the spectra+UB, we perform pPXF fitting with third-order regularization (Boecker et al. 2020) to iteratively find the best regularization parameter for each spaxel. The emission lines are masked out at this point. The best regularization parameter should increase the $\chi^2$ by $\Delta \chi^2 \approx \sqrt{2N}$ compared to the unregularized best fitting, where $N$ is the number of wavelength pixels used in the fitting. The most likely nonparametric star formation histories are derived based on this final round of pPXF fitting.

3.2. Detection and stellar population fitting of star clusters

Star clusters are the best approximation to SSPs, and their distribution, although being affected by cluster dissolution processes, provides a relatively clean view of the star formation histories of their host galaxies. To maximize the cluster-detection efficiency in NGC 2915, we create a new data cube by combining

\[ \text{Subtraction: } \frac{S}{N} \gtrsim 3 \text{ near } 5500 \text{ Å} \]

\[ \text{Masking: } \frac{S}{N} < 50 \text{/Å} \]

\[ \text{Binning: } 0.6′′ \times 0.6′′ \]

\[ \text{Modeling: } \text{SSP models from MILES} \]

\[ \text{Correction: } \Delta \chi^2 \approx \sqrt{2N} \]

\[ \text{Selection: } N \text{ number of wavelength pixels} \]

\[ \text{Detection: } \text{Star clusters} \]

\[ \text{Aromatic: } 0.6′′ \times 0.6′′ \]

\[ \text{Synthesis: } \text{FSPS, Conroy et al. 2009} \]

\[ \text{Velocity: } \chi^2, \text{DOF = 1} \]

\[ \text{Reduction: } \text{Calzetti et al. 2000} \]

\[ \text{Correction: } \text{third-order regularization} \]

\[ \text{Detection: } \text{Star clusters} \]

\[ \text{Aromatic: } 0.6′′ \times 0.6′′ \]

\[ \text{Synthesis: } \text{FSPS, Conroy et al. 2009} \]

\[ \text{Velocity: } \chi^2, \text{DOF = 1} \]

\[ \text{Reduction: } \text{third-order regularization} \]
Fig. 2. Distribution of the compact sources detected based on the MUSE V-band image. Different types of sources are plotted with different symbols, as indicated in the legend. The background is the V-band image whose diffuse stellar light has been subtracted (see Section 3.2). Bright star clusters ($V < 22.8$ mag), faint star clusters ($V > 22.8$ mag), stars, and background galaxies are shown as green filled circles, green open circles, red crosses, and blue squares.

Detection. In order to better reveal star clusters, we use the Background2D task in the Photutils package to create a 2D map of the diffuse "background" light, with the parameter box_size set to $10 \times 10$ pixels, and subtract this 2D background map from the V-band image. Next, the background-subtracted V band image is used for cluster detection with the DAOFIND algorithm (Stetson 1987). A total of 127 cluster candidates at least $5\sigma$ above the local background are found. In order to estimate the completeness limit of our cluster detection, we adopt the artificial-star-test method, and find a $90\%$ completeness limit at $V \leq 22.8$ mag (Figure 3).

Spectro-photometric extraction. A PSF-weighted aperture photometry is performed for the 127 cluster candidates in each wavelength slice of the original data cube. The PSF-weighted photometry is equivalent to the optimal extraction algorithm commonly used in long-slit spectroscopy. A Gaussian PSF model with FWHM = $1.2''$ and a cutoff radius of $2.4''$ is adopted in the photometry. The local background for each cluster candidate is estimated with a circular annulus of inner radius of $2.2''$ and outer radius of $2.6''$, and the background spectrum is a median of all spaxels in the circular annulus. The same aperture photometry is also performed on the HST $U$ and $B$-band images.

Sample cleaning. The above-selected sample of cluster candidates is subject to contamination by single stars and background galaxies. We adopt two criteria to remove contaminants. First, the sources with radial velocities of greater than 150 km/s lower or higher than the systemic velocity of NGC 2915 ($\simeq 465$ km/s) are regarded as foreground stars or background galaxies. Second, as typical star clusters at the distance of NGC 2915 are expected to be at least partially resolved on the HST images, sources with concentration indices $CI_{2-3.5}$ measured on the HST
white-light images (a combination of F336W, F439W, F555W, and F814W) smaller than 0.75 are regarded as single stars, where CI$_{2-3.5}$ is the magnitude difference between an aperture of 2 pixels in radius and one of 3.5 pixels in radius. The CI$_{2-3.5}$ criterion is based on the CI$_{2-3.5}$ distribution of foreground stars confirmed with radial velocities in the NGC 2915 field. By applying the two criteria to the candidate sample, we are left with 78 confirmed star clusters, of which 49 are brighter than the 90% completeness limit of the cumulative distributions of $\text{exp}(>-\chi^2/2)$ for ages and metallicities respectively.

4. Results

4.1. Kinematics

4.1.1. The overall velocity gradients: a counter-rotating stellar disk

Velocity fields of stars and ionized gas (as traced by H$\alpha$ and [O III]5007 emission lines) of NGC 2915 are shown in Figure 2. The neutral H$\text{i}$ gas velocity field (synthesized beam $\sim$ 17$''$×18$''$) from Elson et al. (2010) is overplotted as contours. As with the neutral gas, the ionized gas exhibits an obvious southeast–northwest velocity gradient that is approximately along the direction of the photometric major axis and of the H$\text{i}$ kinematic major axis. In contrast to the gas, the stars exhibit a much weaker velocity gradient that appears to be in an opposite sense to the gas.

To further quantify the radial-velocity variations, Figure 5 presents the radial variation of average velocities along 8$''$-wide slits that are aligned with either the photometric major (upper panel) or minor axes (lower panel). We note a negative southeast–northwest stellar velocity gradient, running from $\sim$ 472 km/s at $\sim$ −20$''$ to $\sim$ 460 km/s at $\sim$ 30$''$ along the major axis. By adopting a photometric inclination angle of 55°, the major-axis stellar velocity gradient corresponds to a maximum rotational velocity of $\sim$ 7 km/s within 30$''$. The stellar rotation is not just in the opposite direction to but also significantly lower than the rotational velocities ($\sim$ 19 km/s at 30$''$) derived by tilted-ring fitting to the overall velocity field of the extended H$\text{i}$ disk (Elson et al. 2010). We checked the stellar velocity dispersion profile (not shown here) and found a nearly constant velocity dispersion of 39 km/s across the observed field, with the typical measurement error of $\sim$ 6 km/s and a scatter of $\sim$ 2 km/s along the major axis. The relatively low stellar rotational velocities may be attributed to a more important pressure support. In the stellar velocity map, we note that a small area near $\Delta$(RA) $\sim$ 10$''$ and $\Delta$(Dec) $\sim$ −15$''$ has a significantly higher velocity than its surroundings. This high-velocity “clump” is associated (in projection) with several bright star clusters close to each other.

Fig. 3. $V$-band magnitude distribution of the star clusters in NGC 2915. The cyan curve indicates how completeness changes with source brightness. The red vertical dashed line marks the magnitude limit ($V = 22.8$ mag) corresponding to the 90% completeness. Only the star clusters brighter than this limit are used for our analysis.
To obtain a clear view of the disturbed gas kinematics, we subtract the stellar velocity field from the gaseous velocity fields and present the velocity difference maps in Figure 6. In Figure 6 the left panel is the map of line-of-sight velocity difference of \( \text{H} \alpha \) (\( \nu_{\text{H} \alpha} \)) and stars (\( \nu_{\text{stars}} \)) at their original spatial resolution, and the middle and right panels are respectively the maps of (\( \nu_{\text{H} \alpha} - \nu_{\text{stars}} \)) and (\( \nu_{\text{HI}} - \nu_{\text{stars}} \)), where the MUSE maps have been smoothed to match the spatial resolution (FWHM \( \sim 18'' \)) of H I data.

The convex iso-velocity contour lines of the \( \text{H} \alpha \) emission to the northwest (middle panel of Figure 5) are in contrast to the concave iso-velocity contour lines (as expected for a circular rotation) of the neutral H I gas there, suggesting that the distribution of H I gas is largely decoupled from the ionized gas along the line of sight. The velocity difference map of (\( \nu_{\text{H} \alpha} - \nu_{\text{HI}} \)) shown in the right panel of Figure 5 more clearly illustrates the decoupling of ionized and neutral atomic gas. On the northwest side of NGC 2915, the major-axis of position–velocity curves of H \( \alpha \) and H I intersect at \( R \sim 15'' \) (Figure 5), which roughly coincides with the peak of the most active star-forming region (Figure 8). The major-axis variation of \( \nu_{\text{H} \alpha} - \nu_{\text{HI}} \) on the northwest side is approximately symmetric with respect to the peak of star formation at \( R \sim 15'' \) (Figure 5). The spatial alignment between the H \( \alpha \) kinematics and the active star-forming regions implies stellar feedback-driven outflows.

In addition to the above difference between the ionized and neutral gas toward the northwest, there are patches of redshifted regions to the east (\( \Delta \text{RA} > 0; \Delta \text{Dec} \sim -5'' - 15'' \)) that are seen in the velocity maps of the ionized gas but not the neutral H I gas. To explore the origin of these redshifted patches, Figure 7 shows the \( \text{H} \alpha \) velocity dispersion map derived from pPXF fitting (lower left panel). Several eastern regions with remarkably higher \( \sigma_{\text{H} \alpha} \) (\( \gtrsim 70 \) km/s) are indicated as A, B, C and D. The right panels of Figures 7 show the line profiles, together with Gaussian profile fitting, of several nebular emission lines of the four indicated regions. For regions A and B which have the highest velocity dispersion, we find double-component emission line profiles. The two kinematic subcomponents have velocity differences of \( \sim 160 \) km/s, and none of them (409 and 579 km/s for the two subcomponents of A, and 387 and 534 km/s for B) are close to the expected disk velocities (\( \sim 460 \) km/s), indicating either expanding super-bubbles or colliding gas clouds (e.g., Nath & Shchekinov 2013; Sharma et al. 2014). Nevertheless, the redshifted subcomponents have lower log([N II] / \lambda 6584 / \text{H} \alpha) values than the blueshifted subcomponents (0.25 \pm 0.12 dex lower...
either single or double Gaussian components. The velocity scale (in km/s) for each spectral line profile is indicated in the right panels. The dashed curves overlaid on the line profiles represent the best fit with either single or double Gaussian components. The velocity scale (in km/s) for each spectral line profile is indicated in the right panels.
4.2. Star formation, age and metallicities

To explore the spatial distribution of the current star formation activities, Figure 8 presents the Hα and [O iii]45007 line intensity maps and the Hα equivalent width EW(Hα) maps. Regions with bright emission lines are the sites with active current star formation. It is clear that the current star formation is concentrated towards the northwest side of the galaxy center, and the most intense star formation (ΔRA ~ −10′′; ΔDec ~ 8″) appears to be associated with the northwest peak of H I column densities.

The light-weighted ages, stellar metallicities and ionized gas (oxygen) metal abundances are shown in Figure 9 and the azimuthally averaged radial profiles of these parameters are presented in Figure 10. The gas metallicities are estimated with the O3N2 method (Alloin et al. 1979), which was recently found to give reliable metallicity estimations even in the low Hα brightness regions where significant contribution from diffuse ionized gas (DIG) may be expected (Kumari et al. 2019; Vale...
specifically, we adopt the formula derived by

\[ 12 + \log(O/H) = 8.505 - 0.221 \times O3N2 \]

where

\[ O3N2 \equiv \log \left( \frac{[O III] \lambda 5007}{H\beta} \times \frac{H\alpha}{[N II] \lambda 6584} \right) \]

the regions with the youngest stellar ages are located in the northwest quadrant and roughly along (albeit with an obvious offset) the photometric major axis. This is in agreement with the distribution of H\alpha and [O\,iii]\lambda 5007 emission lines. The youngest light-weighted stellar ages are \( \geq 30 \) Myr, which is in line with the post-starburst nature of NGC 2915. The azimuthally averaged ages steadily increase with galactocentric radii, in agreement with what is usually found in dwarf galaxies. For the stellar metallicity distribution, the azimuthally averaged profile is nearly flat at R \( \leq 20\arcmin \), beyond which the average metallicities decrease significantly with radius, with a negative gradient of \( \sim -0.73 \) dex/kpc. There is no significant azimuthal variation of stellar metallicities at a given galactocentric radius (Figure 9). The metallicity difference map of the gas and stars is shown in Figure 11.

the most active star-forming sites have lower gas metallicities than their immediate surroundings (right panel of Figure 9). This suggests that recent metal-poor gas inflow has played a role in triggering the active star formation (e.g., Kumar et al. 2017). The radial profile of average gas metallicities appears to be flatter than the stellar metallicity profile, but it has an overall positive gradient of \( \sim 0.14 \) dex/kpc. This positive metallicity gradient confirms the finding of \( \sim 0.12 \) dex/kpc in Werk et al. (2010) based on spectroscopy of five H\,ii regions in NGC 2915.

a positive gas metallicity gradient is not expected for a galaxy whose metal production, mixing and loss are in equilibrium (Sharada et al. 2021). Werk et al. (2010) discussed three possible scenarios to explain the positive gradient: metal mixing across the disk, supernova-driven blowout and fallback, and galaxy interactions. Our kinematic analysis in Section 4.1.2 suggests significant stellar feedback-driven outflows. Metal-enriched gas ejected by the feedback may eventually fall back to the disk, with larger angular momentum and thus larger galactocentric distances than before (e.g., Brook et al. 2012), contributing to a less negative or even positive metallicity gradient. Moreover, in addition to the clear evidence for gas inflow (e.g., Section 4.1.2), signature of gas inflow is implied by the localized gas metallicity drops (right panel of Figure 9). Therefore, metal-poor gas inflow or inflow has also played a role in shaping the gas-phase metallicity gradient. We note that the logarithmic differences between gas-phase and stellar metallicities (both normalized to the solar units; Figures 10 and 11) are \( \sim 0.2 \) dex at small radii (\( < 20\arcmin \)) and \( \sim 0.3-0.5 \) dex at large radii. These differences are \( > 0.5 \) dex smaller than the typical values found in low-mass galaxies (e.g., Lian et al. 2018), implying a strong impact from either metal outflow or gas inflow.

**4.3. Star cluster distribution**

The age–mass distribution and spatial distribution of star clusters above the 90\% completeness detection limit are shown in Figure 12. The maximum cluster mass per logarithmic time interval is expected to increase with age (\( M_{\text{max}} \propto \text{Age} \)) for a cluster mass function with a fiducial power-law slope of \( -2 \) (Krumholz et al. 2019) if the cluster formation rate is constant with time. A comparison with the \( M_{\text{max}} \)– Age relation implies that the age–mass distribution of the star clusters in NGC 2915 is inconsistent with a constant cluster formation history. There is an obvious enhancement of cluster formation at \( \sim 10 \)–\( 100 \) Myr ago. In addition, the most massive cluster is \( \sim 2 \) Gyr old, implying a lower cluster formation rate at earlier times (more than a couple of gigayears). The long-term dynamical dissolution effect (Baumgardt & Makino 2003) on our clusters is not important above the 90\% completeness limit, as indicated in Figure 12. We note that, although a quantitative understanding of the observed age–mass distribution of star clusters may be hindered by various very uncertain disruption and fading effects (e.g., Elmegreen...
the region with the highest $H_\alpha$ in the southwestern half of the galaxy. The spatial concentration of clusters largely coincides with the active star-forming area (Section 4.2). With that said, the region with the highest $H_\alpha$ equivalent width ($\Delta(\text{RA}) \sim -10''$; $\Delta(\text{Dec}) \sim 8''$) has lower spatial concentration of clusters than regions at smaller galactocentric distances along the major axis, suggesting that the most active star formation very recently propagated to the current site from smaller galactocentric distances. Finally, we note that the two most massive clusters lie outside the active star-forming area.

4.4. Star formation history

4.4.1. Spatially resolved star formation histories

Spatially resolved star formation histories derived from pPXF fitting are presented in Figure 13. In order to alleviate the potential degeneracies between the estimate of star formation rate in adjacent age bins, we analyze the cumulatively averaged star formation histories. Surface density distribution of star formation rate or stellar mass averaged in cumulatively broader age bins (i.e. $\leq 10^7$ yr, $\leq 10^8$ yr, $\leq 10^9$ yr and throughout the whole lifetime) are shown in different panels of Figure 13.

We perform exponential radial profile fitting to the four maps shown in Figure 14 and find scale lengths of 3.9, 4.5, 11.1, and 18.4 arcsec respectively for the four age intervals. This means younger stellar populations are more spatially confined towards the central region of NGC 2915, which implies that either the star formation activities have become more and more centrally concentrated over time or older stars have had more time to migrate or disperse to larger radii. Nevertheless, the spatial distribution of star formation is not uniform along the azimuthal direction, as indicated by the iso-$S_{\text{SFR}}$ contours in Figure 13. When averaged over the past $10^8$ yr, the southeastern side of NGC 2915 appears to have higher $S_{\text{SFR}}$ than the other side. Over the past $10^7$ yr, the northwestern side has significantly stronger $S_{\text{SFR}}$ than the southeastern side, as opposed to the average over $10^9$ yr timescales. In the last $10^7$ yr, star formation has continued to be more active in the northwestern side of the galaxy, and at the same time has been significantly enhanced along a $\sim 5''$-wide ($\sim 0.1$ kpc) stripe that is parallel to the direction of the major axis. The linear correlation of the stellar line-of-sight velocities with the radius shown in Figure 5 suggests a solid-body rotating stellar disk, as with the solid-body $H_\alpha$ rotation curve within the central $\sim 3$ kpc (Elson et al. 2010), so the above-mentioned azimuthal asymmetry is (in a relative sense) not subject to significant rotational mixing.

4.4.2. Global star formation history

The global star formation history of NGC 2915 is derived by integrating the spatially resolved star formation histories and shown as blue curves in Figure 14. In addition, number counts of clusters in logarithmic age intervals are overplotted as red curves in the lower panel of Figure 14. As a compromise between sample size, completeness and lookback time, here we only consider clusters more massive than the 90% completeness limit at the age of $10^9$ yr ($\sim 1.25 \times 10^4 M_\odot$, Figure 12).

Theoretical studies suggest that cluster dissolution or fading may result in a approximately uniform log(Age) distribution of clusters for a constant cluster formation history (e.g., Elmegreen & Hunter 2010), and therefore deviations of the observation from a uniform distribution may indicate a nonconstant cluster formation history. It is encouraging to see that the overall trend of cluster distribution roughly matches that of the star formation history derived from full-spectrum fitting for NGC 2915. Cluster distributions have been used to probe the star formation histories of interacting galaxies in the literature (e.g., Bastian et al. 2005; Zhang et al. 2020a). Nevertheless, it is unclear to what extent (and how) the observed cluster distributions have been affected by disruption or fading effects, so it is not straightforward to convert the observed number counts to cluster formation rates.

Fig. 12. Star cluster distributions of NGC 2915. Top: Distribution of star clusters in the mass-age plane. The plotted mass is the mass at birth. Each circle is a star cluster color-coded by its metallicity. The purple solid curve is the 90% mass completeness limit converted from the $V = 22.8$ mag brightness limit by using age-dependent mass-to-light ratios. The purple dashed line is plotted as a guide for the expected relation between maximum cluster mass and age by assuming a fiducial cluster mass function and constant cluster formation history. The dynamical evaporation limit is derived using a galactocentric radius of 0.47 kpc (24 arcsec) and a rotation velocity of 15 km/s, as appropriate for the inner disk of NGC 2915. Bottom: Spatial distribution of star clusters color-coded by the stellar age. The filled circles are plotted with sizes proportional to the fourth root of stellar mass. The EW($H_\alpha$) distribution is overplotted as contours.

& Hunter 2010, the features for NGC 2915 mentioned above cannot be easily explained by any known disruption mechanism.

Spatial distribution of the clusters is highly asymmetrical about the major axis (lower panel of Figure 12), with more clusters in the southwestern half of the galaxy. The spatial concentration of clusters largely coincides with the active star-forming area (Section 4.2). With that said, the region with the highest $H_\alpha$ equivalent width ($\Delta(\text{RA}) \sim -10''$; $\Delta(\text{Dec}) \sim 8''$) has lower spatial concentration of clusters than regions at smaller galactocentric distances along the major axis, suggesting that the most active
The global star formation history peaked around ~ 2 Gyr ago, which is also when the most massive cluster in NGC 2915 formed (Figure 12). In the last ~ 1 Gyr, the global star formation rate has been declining and ~ 10% of the total stellar mass was formed. The most recent episode of active star formation reached its maximum around ~ 50 Myr ago (lower panel of Figure 14), with a duration of ~ 50 Myr, and has formed ~ 3% of the total stellar mass. The cluster age distribution also peaks at ~ 50 Myr or so, in broad agreement with the recent star formation history.

It is conceivable that episodes of bursty star formation like the most recent one may have recurred in the past, but the coarser time resolution at older ages precludes us from recovering them. Nevertheless, we can estimate that such bursty star formation events have recurred less than 4 times (10%/3%) in the past 1 Gyr. Our spatially resolved star formation histories and the distribution of star clusters (Section 4.3) imply that recurrence of bursty star formation episodes occurred in different spatial locations.

4.5. Excitation sources of the gaseous nebulae: no evidence for an active galactic nucleus

In order to explore the excitation mechanisms of the gaseous nebulae in NGC 2915, we turn to the three commonly used line-ratio diagnostic diagrams (Veilleux & Osterbrock [1987]), involving [O ii]/Hα, [N ii]/Hα, [S ii]/Hα, and [O i]/Hα. The [O iii]/Hβ versus [N ii]/Hα diagram is known as the BPT diagram (Kewley et al. [1998]), which is one of the most important diagnostics for distinguishing the excitation by star formation and active galactic nuclei (AGN). [S ii] and [O i] lines are produced by partially ionized zones of gaseous nebulae and are not as sensitive to metallicities as [N ii], which makes them ideal tracers of shocks and weak or low-metallicity AGNs.

Figure 15 shows the distribution of the Voronoi-binned spaxels of NGC 2915 on the three diagnostic diagrams. The data points are color-coded by galactocentric radius and only spaxels with S/N > 10 in all the six involved emission lines are plotted. Almost all of the spaxels in NGC 2915 are well below the theoretical “maximum starburst line” (Kewley et al. [2001]) and are also below the Kaufmann et al. (2003) empirical “purely star-forming line” on the BPT diagram. On the other two line-ratio diagrams, a fraction of spaxels fall into the regime of AGN- or LINER-like excitation, and the fraction is higher in the [O iii]/Hβ versus [O i]/Hα diagram. All but several unconnected spaxels with AGN- or LINER-like spaxels are distributed at large galac-
tocentric distances (rightmost panel of Figure 16), which basically rules out AGN as a possible excitation source.

We also make an attempt to search for the forbidden high-ionization coronal lines (e.g., [Fe VII]λ6087, [Fe X]λ6374, [Fe XI]λ7892) that have ionization potentials $\gtrsim$ 100 eV (e.g., Getford et al. 2009, Negus et al. 2021). Detection of these emission lines is considered to be a signature of AGN activity (e.g., Molina et al. 2021). No such emission lines with S/N $> 3$ are detected across the observed field, again disfavoring the presence of an AGN.

While there is no evidence for an AGN, excitation sources other than pure star formation, such as shocks, are still possible. In the two diagnostic diagrams involving [S II] and [O I] lines, the Allen et al. (2008) shock and shock+precursor models (with one-fifth of solar metallicity) overplotted in the middle and right panels of Figure 15 appear to explain the excitation of spaxels above the maximum starburst line to a great extent. Figure 16 further shows the line-ratio maps, where the highest values of the shock-sensitive [S II]/Hα and [O I]/Hα are found at the outer edges of the observed field. Similar findings are also reported in several other dwarf galaxies (Fensch et al. 2016, Cairós & González-Pérez 2017a, Bik et al. 2018). Nevertheless, an inspection of the emission line velocity dispersion map (Figure 7) reveals that the regions with the highest [S II]/Hα and [O I]/Hα tend to have relatively low velocity dispersion (≤ 30 km/s), which raises doubt about their shock-excited nature and instead favors diffuse ionized gas (possibly) ionized by photons leaking from H II regions.

5. Summary
In this work, we used the deep integral field spectroscopic data from the VLT/MUSE instrument to investigate the kinematics, stellar populations, and excitation sources of the blue compact dwarf galaxy NGC 2915. The MUSE observations cover the inner exponential disk of the galaxy. In particular, we performed a joint fitting of the MUSE spectra and HST broadband pho-
tometry to obtain the spatially resolved star formation histories, studied the spatial distribution and stellar populations of bright star clusters ($V < 22.8$ mag; $M_V < -5.3$ mag) detected based on the MUSE data, compared the stellar and gaseous kinematics, and explored the excitation sources of the gaseous nebulae based on the classical line-ratio diagnostic diagrams. Our main results are summarized below.

1. The stellar disk exhibits a relatively weak but significant rotation within the central ~0.5 kpc in radius. The stellar rotation axis appears to be anti-parallel to that of the extended neutral H i disk (Section 4.1.1). The kinematics of the ionized gas is significantly disturbed either by stellar feedback associated with the active star formation or gas inflow/outflow. In contrast to the ionized gas, the neutral H i gas does not appear to deviate significantly from regular rotation (e.g., Figure 1), implying that the two gas phases are largely spatially decoupled along the line of sight.

2. The global star formation history peaked around a couple of gigayears ago (Section 4.2). The massive star clusters (Section 4.2) were then formed. The most recent episode of bursty star formation happened around ~50 Myr ago and has lasted for ~50-100 Myr. It is intriguing to note that the observed cluster age distribution roughly follows the trend of star formation histories. This recent episode of bursty star formation has formed ~3% of the total stellar mass. Episodes of bursty star formation similar to the most recent one may have recurred less than 4 times in different locations (but largely confined within the central 0.4 kpc in radius) in the past 1 Gyr.

3. The average stellar metallicities have a nearly flat radial profile in the central 0.4 kpc in radius, beyond which the metallicities drop steeply with radius. In contrast to the stellar metallicities, the average gas-phase metallicities have a positive radial gradient ($\sim 0.14$ dex/kpc), which is unexpected for a system whose metal production, mixing, and loss are in equilibrium. This confirms the finding of Werk et al. (2010) based on spectroscopy of five H ii regions. We found evidence for both metal-rich gas outflow and metal-poor gas inflow that may collectively contribute to the positive gas-phase metallicity gradient. In particular, the metal-poor gas inflow is unveiled by both signatures of cloud–cloud collisions (Section 4.1.3). An unusually small difference between the gaseous and stellar metallicities (Section 4.2) also points to either significant inflow or outflow.

4. Based on the classical line-ratio diagnostic diagrams of Veilleux & Osterbrock (1987), no evidence for an AGN is found in NGC 2915 (Figures 13 and 16). Regions outside the active star-forming area tend to have higher $[\alpha /Fe]$, with $[\alpha /H_\alpha]$ line ratios but lower gas velocity dispersions ($\leq 30$ km/s) than the central regions, suggesting a dominant contribution from diffuse ionized gas.

The analysis presented in this work points to a highly complex inner disk of NGC 2915 in terms of the relative distribution of stars and gas. Indeed, Elson et al. (2010) found that the complex H i gas distribution of the inner ~2 kpc cannot be explained by either pure circular rotation (even allowing for radial variation of disc inclinations) or highly turbulent velocity dispersion. There are at least two nonaxisymmetric H i features in the central ~2-3 kpc, one is a stream-like feature in the southeast along the major axis that is visible in the velocity field and causes an abrupt decline in radial velocities (Section 4.1.1), and the other is a plume-like feature in the northwest also along the major axis that is visible in the column density and moment-2 map (Elson et al. 2010). These features demonstrate an ongoing tidal interaction or gaseous accretion. The discovery of a counter-rotating central stellar disk implies an external origin of the gaseous material that has sustained the recent episodes of bursty star formation.

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References

Allen, M. G., Groves, B. A., Dopita, M. A., Sutherland, R. S., & Kewley, L. J. 2008, ApJS, 178, 20, doi: 10.1086/598952
Allende Prieto, C., Lambert, D. L., & Asplund, M. 2001, ApJ, 556, L63, doi: 10.1086/322874
Allom, D., Collin-Souffrin, S., Joly, M., & Vigroux, L. 1979, A&A, 78, 200
Bastian, N., Gieles, M., Lamers, H. J. G. L. M., Scheepmaker, R. A., & de Grijs, R. 2005, A&A, 431, 905, doi: 10.1051/0004-6361:20041878
Baumgardt, H., & Makino, J. 2003, MNRAS, 340, 227, doi: 10.1046/j.1365-8711.2003.06286.x
Becker, K., Mebold, U., Reif, K., & van Woerden, H. 1988, A&A, 203, 21
Bekki, K. 2008, MNRAS, 388, L10, doi: 10.1111/j.1745-3933.2008.00489.x
Berk, A., Ostlin, G., Menacho, V., et al. 2018, A&A, 619, A13, doi: 10.1051/0004-6361/201833916
Becker, K., Leaman, R., van de Ven, G., et al. 2020, MNRAS, 491, 823, doi: 10.1093/mnras/stz3977
Brinks, E., & Klein, U. 1988, MNRAS, 231, 63P, doi: 10.1093/mnras/231.1.63P
Brook, C. B., Stinson, G., Gibson, B. K., et al. 2012, MNRAS, 419, 771, doi: 10.1111/j.1365-2966.2011.19748.x
Bureau, M., Freeman, K. C., Pfitter, D. W., & Meurer, G. R. 1999, AJ, 118, 2185, doi: 10.1086/301064
Caríos, L. M., & González-Pérez, J. 2013a, A&A, 559, A13, doi: 10.1051/0004-6361/201321293
Caríos, L. M., Vílchez, J. M., González-Pérez, J. N., Iglesias-Páramo, J., & Casas, N. 2001, ApJS, 133, 321, doi: 10.1086/128354
Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, ApJ, 533, 682, doi: 10.1086/368692
Cappellari, M. 2017, MNRAS, 466, 798, doi: 10.1093/mnras/stw3926
Cappellari, M., & Copin, Y. 2003, MNRAS, 342, 345, doi: 10.1046/j.1365-8711.2003.06541.x
Cappellari, M., & Emsellem, E. 2004, PASP, 116, 138, doi: 10.1086/381875
Conroy, C., Gunn, J. E., & White, M. 2009, ApJ, 699, 486, doi: 10.1088/0004-637X/709/1/486
Corwin, H. G., de Vaucouleurs, A., & de Vaucouleurs, G. 1985, Southern galaxy catalogue. A catalogue of 5481 galaxies south of declination -17 grad. found on 1.2m UK Schmidt Illa J plates
Elmegreen, B. G., & Hunter, D. A. 2010, ApJ, 712, 604, doi: 10.1088/0004-637X/712/1/604
Elmegreen, B. G., & Zhang, H.-X., & Hunter, D. A. 2012, ApJ, 747, 105, doi: 10.1088/0004-637X/747/2/105
Elson, E. C., de Blok, W. J. G., & Kraan-Korteweg, R. C. 2010, MNRAS, 404, 2061, doi: 10.1111/j.1365-2966.2010.16422.x
Elson, E. C., de Blok, W. J. G., Kraan-Korteweg, R. C. 2010, MNRAS, 404, 2061, doi: 10.1111/j.1365-2966.2010.16422.x
Fensch, J., Duc, P. A., Weilbacher, P. M., Boquien, M., & Zackrisson, E. 2016, A&A, 585, A79, doi: 10.1051/0004-6361/201527141
Gebhardt, J. M., Mullaney, J. R., & Ward, M. J. 2009, MNRAS, 397, 172, doi: 10.1111/j.1365-2966.2009.14961.x
Hunt, D. A., & Elmegreen, B. G. 2004, AJ, 128, 2170, doi: 10.1086/424015
Izotov, Y. I., & Thuan, T. X. 1999, ApJ, 511, 639, doi: 10.1086/396708

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