A 39 kpc Spatially Extended Clumpy and Asymmetric Galactic Outflow Imaged with Mg II Emission

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ABSTRACT

We image the spatial extent of a cool galactic outflow with resonant Mg II emission in a gravitationally lensed star-forming galaxy at z ∼ 1.7 using VLT/MUSE observations. We observe Mg II residual (continuum-subtracted) emission out to an observed radial distance of 26.5±0.5 kpc from the galaxy, with an observed maximum spatial extent of ≈ 39±0.8 kpc (30±0.7 kpc after correcting for seeing). Mg II residual emission is patchy and covers a total area of 184±5 kpc², constraining the minimum area covered by the outflowing gas to be 13.27±0.55% of the total area. The spatial extent of the Mg II emission is asymmetric and shows an observed 27.6±0.8% (20.9±0.7% after seeing correction) larger extent along the declination direction. We constrain the covering fraction of the Mg II emission as a function of radial distance and characterize it with a power-law model convolved with the seeing with an index γ = −1.25±0.02. We find two kinematically distinct Mg II emission components (∆v ≈ 400 km s⁻¹) which extend out to similar distances, and may correspond to two distinct shells of outflowing gas. By using multiple images with different magnifications of the galaxy in the image plane, we trace the Mg II residual emission in three individual star-forming regions inside the galaxy out to 6.0±0.2, 7.0±0.3, and 8.5±0.4 kpc. Both the Fe II* fine structure emission, and the nebular [O II] emission are not spatially extended relative to the stellar continuum. These findings provide robust constraints on the spatial extent of the outflowing gas and combined with outflow velocity and column density measurements will give stringent constraints on mass outflow rates of the galaxy.

Keywords: galaxies: starburst; galaxies: general; galaxies: evolution; gravitational lensing: strong; galaxies: intergalactic medium

1. INTRODUCTION

Galactic outflows play an important role in galaxy evolution (Somerville & Davé 2015) as they transport baryons from the inter-stellar medium (ISM) of galaxies into their circumgalactic medium (CGM; Bordoloi et al. 2011; Tumlinson et al. 2017; van de Voort 2017; Anglés-Alcázar et al. 2017). This process depletes the
gas supply needed to form the next generation of stars in star-forming galaxies and in extreme cases, can completely quench star-formation in them (Man & Belli 2018; Geach et al. 2018; Hopkins et al. 2012, 2014). By carrying metals out from the ISM, these outflows can also enrich the intergalactic medium (IGM; Rahmati et al. 2016; Ford et al. 2016; Rupke 2018). The energy sources driving these outflows can be either star formation (SF) or active galactic nuclei (AGNs) in the galaxy (Veilleux et al. 2005). In this work, we will only focus on star-formation driven outflows.

Theorists debate whether star-formation driven galactic outflows are powered by energy from supernovae explosions (Chevalier & Clegg 1985) or momentum from high-energy photons, and stellar winds, or cosmic rays (Murray et al. 2005). The outflows also seem to regulate the star formation and set the mass-metallicity relation (Tremonti et al. 2004). These outflows are also ubiquitous in star-forming galaxies and are complex and multi-phased, by which we mean both ionized and neutral gas with significant dust (Veilleux et al. 2005; Weiner et al. 2009; Rubin et al. 2010; Martin et al. 2013; Bordoloi et al. 2014; Chisholm et al. 2015; Heckman et al. 2015; Fiore et al. 2017; Bordoloi et al. 2017; Cicone et al. 2018; Rupke 2018; Schneider et al. 2018). These different phases of outflow can be detected at many wavelengths ranging from the X-rays to millimeter and sub-millimeter (Rupke 2018).

While models and simulations require outflows to regulate the star formation within galaxies, constraining the impact of outflows requires estimating the total mass that outflows carry out of galaxies. The rate of mass loss is typically characterized by the mass outflow rate ($\dot{M}_{\text{out}}$), as,

$$\dot{M}_{\text{out}} = \Omega \cdot C_f \cdot \mu m_p \cdot N_H \cdot r \cdot v_{\text{out}},$$

where $\Omega$ is the opening angle of the outflowing gas, $C_f$ is the covering fraction or the ratio of the stellar continuum that is covered by the outflow in the context of the “down-the-barrel” observations, $\mu m_p$ is the mean molecular weight of Hydrogen, $N_H$ is the column density of the outflowing gas, $v_{\text{out}}$ is the velocity of the outflowing gas, and $r$ is the distance or the spatial extent of the outflow from the galaxy. The parameters of equation 1 can be observationally constrained in robust manner from down-the-barrel spectroscopic studies of galactic outflows (Chisholm et al. 2016b). However, the spatial extent ($r$) of the outflow remains largely unconstrained in such works. Therefore, different strategies have been implemented to infer $r$ (Rubin et al. 2014; Heckman et al. 2015; Bordoloi et al. 2016; Chisholm et al. 2016a, 2018). One way to make progress is to use spatially extended emission lines (Hα, O II, Mg II, Fe II*, etc.) that trace the densest phase of the gas in such outflows, to measure the corresponding spatial extent of the outflowing gas (Shapley et al. 2003; Rubin et al. 2011; Zhang et al. 2016; Rupke et al. 2019; Burchett et al. 2021; Zabl et al. 2021).

This has been done for galaxies in the local universe and galaxies at moderate redshift ($z \approx 0.5$). Rubin et al. (2011) used Keck/LRIS to measure the spatial extent of the wind in the galaxy TKRS4389 ($z \approx 0.47$). The measured extent of the Mg II emission doublet 2796, 2803 Å from the wind is $\sim 7$ kpc in one dimension along the slit. The limited slit size will lead to the loss of the signal from the Mg II emission from the regions of the galaxy which are not covered by the slit. One can increase the spatial coverage by performing integral field unit (IFU) spectroscopy, which provides a spectrum for each spaxel in the field of view.

Indeed Burchett et al. (2021) targeted the same galaxy with KCWI/IFU observations and measured a $\sim 31$ kpc spatial extent of the Mg II emission. Rupke et al. (2019) studied another galaxy at similar redshift $z \approx 0.46$ using KCWI. They measured the spatial extent of the wind traced by the [O II] doublet 3726, 3729 Å and detected the emission up to $\sim 100$ kpc, which is the largest measured extent of a galactic outflow. Other Mg II IFU observations of extreme galaxies have shown that some galaxies do not have extended Mg II outflows, rather strong Mg II emission can arise in H II regions within galaxies (Chisholm et al. 2020).

One of the complexities in tracing outflows using emission lines is the low surface brightness emission in individual galaxies. This makes it hard to detect the emission and localize it to the individual star-forming clumps which might be driving the outflowing gas. To overcome these issues we can leverage the phenomenon of gravitational lensing and zoom-in on individual star-forming regions in a galaxy (Bordoloi et al. 2016). Gravitational lensing stretches sub kpc-scale regions within a galaxy to few arc-seconds on the sky while conserving the surface brightness of each region. This is very suitable for studying individual star-forming regions within a galaxy, especially when the lensed galaxy have multiple images in the image-plane. One of the conditions for this method to work, is that the lens should have a robust mass model (Sharon et al. 2012, 2020). Augmented with deep IFU observations, we can obtain very high signal-to-noise-ratio (SNR) observations with large spatial coverage and constrain the properties of galactic outflows at different sizes and scales in the source plane of the galaxies driving them. By using the lens model with the IFU observations, we can trace the 2D maps
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of the emission lines tracing the outflows to the source plane of the galaxy and obtain a measure for the outflow extent in physical distance.

In this work, we use VLT/MUSE observations to study the Mg II resonant back scattered emission, and the Fe II* fine structure emission in the strong gravitationally lensed galaxy RCSGA 032727-132609 at $z \sim 1.703$ (Wuyts et al. 2010, 2014). The Mg II and Fe II* emission trace the cool phase of the outflows. We also study the nebular [O II] emission. We measure the spatial extent of the outflow using the Mg II emission. The detailed study of outflow gas kinematics and mass outflow rates will be presented in a separate forthcoming publication (Shaban et al. in prep).

This paper is organized as follows: §2 describes the MUSE observation; §3 describes the process of mapping the Mg II and Fe II* emission in the image plane, the construction of these maps in the source plane, and the surface brightness radial profiles extraction; §4 describes the results of the analysis. In §5, we discuss these results, compare them with the literature, and state the final conclusions of our study. For the rest of this work, we do our calculations assuming a Λ-Cold Dark Matter (ΛCDM) cosmology with $H_0 = 70$ km s$^{-1}$Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

2. OBSERVATIONS

The galaxy RCSGA 032727-132609 is a low-metallicity star-forming galaxy at $z \approx 1.703$ (González-López et al. 2017; Rigby et al. 2018) and is lensed by the galaxy cluster RCS2 032727-132623 at $z = 0.564$ (Wuyts et al. 2010, 2014). It was discovered in the Second Red Sequence Cluster Survey (Gilbank et al. 2011). The apparent shape of the galaxy consists of the main arc north of the cluster subtending 38″ and a smaller counter arc south of the cluster subtending 7″ on the sky (see Figure 1; Wuyts et al. 2014). The main arc consists of three images of the galaxy (images 1, 2, and 3) denoted by yellow rectangles and yellow numbers in Figure 1 and the counter arc is a 4th image. Image 1 and Image 2 are highly magnified because they are situated near the critical lines in the image plane. Images 1 and 2 represent sub-regions of the galaxy in the image plane. These critical lines correspond to the regions, where there is theoretically infinite magnification. From the best fit model for the lens from Sharon et al. (2012), the average magnification across the main arc is $25.1^{+2.2}_{-2.5}$, and the average magnification values of the individual images of the main arc are $10.4^{+1.3}_{-1.2}$, $20.6^{+4.6}_{-2.2}$, and $9.7^{+1.1}_{-0.5}$ for images 1, 2, and 3, respectively. The magnification of the counter arc is $3.0^{+0.9}_{-0.1}$.

This paper focuses on IFU observations of RCSGA 032727-13260 using the VLT/MUSE instrument with program ID: 098.A-0459(A) (Lopez et al. 2018). The observations were taken using the MUSE wide field mode with a spatial sampling of 0.2″ per pixel, a field of view of $1' \times 1'$, and spectral sampling of 1.25 Å per pixel and a spectral resolution ($R = \frac{\lambda}{\Delta \lambda}$) of 1770 at 480 nm to 3590 at 930 nm (Bacon et al. 2010). The total exposure time of the observations is 3.1 hours. During the time of the observations, the maximum atmospheric seeing was 0.8″ and the maximum airmass was 1.8. The sky subtraction was applied on the cube using the Zurich Atmospheric Purge (ZAP) algorithm (Soto et al. 2016). We refer the reader to Lopez et al. (2018) for a detailed description of the observations. We use Hubble Space Telescope WFC3/F390W, WFC3/F606W, and WFC3/F814W imaging of this field (PI: J. Rigby, Proposal ID: 12267) to construct a multi-wavelength composite image of the main arc and the counter arc (Figure 1). The observed pivot wavelengths for these filters correspond to galaxy rest-frame wavelengths of 1450 Å, 2176 Å, and 2976 Å, respectively. We use these HST observations to accurately define the astrometry of the MUSE data-cube. We identify three common bright stars in both the MUSE data-cube and the HST images. Then, we match their central pixel coordinates to fix the astrometric offset in the MUSE data-cube. These offsets correspond to a difference in right ascension $\Delta\alpha \approx 0.693''$, and a difference in declination $\Delta\delta \approx 3.157''$, respectively.

Figure 1 shows the main arc in the top row and the counter arc in the bottom row with the multiple images of the galaxy shown in yellow dashed rectangles for both MUSE white light image (left panels) and the HST composite image (right panels). We follow the naming convention of the star-forming (SF) regions from Bordoloì et al. (2016). There are four SF regions named E, U, B, and G that are multiply imaged in the main arc. They are highlighted with purple arrows in Figure 1. Image 2 is the most magnified image and image 1 is the second most magnified image and both of them represent small individual star-forming regions in the source plane galaxy. Image 3 and the counter arc represent images of the whole galaxy in source plane. The counter arc is the least magnified and least distorted image of the galaxy and we use it as a representative of our measurements for the whole galaxy.

3. METHODS

We aim to estimate the spatial extent of galactic outflows in this galaxy using the Mg II and Fe II* emission lines. For this purpose, we produce narrow band maps
around the emission lines of interest. We use the lens model to reconstruct these emission maps in the source plane of the galaxy and measure the true physical extent of the outflows. We develop and use a python package to do most of this analysis named *musetools*. These steps are described as below.

3.1. 1D Spectral Extraction

To identify the emission lines of interest, we extract a light weighted 1D spectrum of the main arc of the galaxy. We first select the voxels, which are the data points in the datacube, that cover the main arc. These voxels are summed over the 4600–9350 Å wavelength range to create a white light image of the arc. Each voxel is weighted by this white light image and summed in the spatial direction to create a light weighted 1D spectrum of the arc. This method produces a high SNR 1D spectrum of the galaxy and is shown in Figures 2 and 3. The emission lines of interest for this study are the Mg\(\text{II}\) emission doublet \(\lambda\lambda\ 2796, 2803\) Å, five Fe\(\text{II}^*\) fine structure emission lines, and the [O\(\text{II}\)] nebular emission doublet \(\lambda\lambda\ 2470, 2471\) Å (Morton 2003; Leitherer et al. 2011). These lines are summarized in Table 1. The Mg\(\text{II}\) and Fe\(\text{II}^*\) emission trace the outflows and the [O\(\text{II}\)] emission traces the star-forming regions in the galaxy. The Mg\(\text{II}\) emission doublet shows a P-Cygni profile with the Mg\(\text{II}\) absorption lines. A selection of the specific wavelength intervals for Fe\(\text{II}^*\) and Mg\(\text{II}\) emission is shown in Figures 2 and 3, respectively. The [O\(\text{II}\)] emission lines show up as a blended doublet highlighted in green in Figure 2. The average SNR per pixel for the entire spatially-summed region for the Fe\(\text{II}^*\), [O\(\text{II}\)], and Mg\(\text{II}\) lines are 94, 106, and 74, respectively.

3.2. Generating Emission Maps

To produce narrow band maps around an emission line of interest, we follow the following procedure.

- We select a wavelength window over which a narrow band image is to be created (see Table 2, Figure 2, and Figure 3).
- We sum all the flux voxels in that wavelength window and multiply by the width of the window \(\Delta\lambda\) and divide by the angular area of each pixel (pixel area \(\Delta xy = (2')^2\)) to create a narrow band surface brightness image of the emission line and the

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1 https://github.com/rongmon/musetools
underlying continuum of the galaxy.

\[ SB_{(i,j)} = \sum_{l=\lambda_{min}}^{l=\lambda_{max}} f_{(l,i,j)} \times \frac{\Delta \lambda}{\Delta xy} \]  

(2)

where \( SB_{(i,j)} \) is the surface brightness at the \((i,j)\)th pixel measured in units of \( \text{erg} \, \text{s}^{-1} \, \text{cm}^{-2} \, \text{arcsec}^{-2} \), \( f_{(l,i,j)} \) is the flux density at the \((l, i, j)\) voxel measured in units of \( \text{erg} \, \text{s}^{-1} \, \text{cm}^{-2} \, \text{Å}^{-1} \).

- We create a pure continuum emission map by specifying another wavelength interval redward of the emission lines (Table 2) that has a wavelength window of identical width (\( \Delta \lambda \)) as the one chosen for the previous step. These voxels are summed to create a pure continuum surface brightness map of the galaxy. As young stellar populations have very featureless continuum regions in the rest frame 2000-3000 Å range, this method creates robust continuum maps (Leitherer et al. 1999).

- We subtract the emission+continuum images with the pure continuum images to produce a continuum subtracted residual emission maps.

We define an average background surface brightness noise level for each map to quantify the statistical significance of individual emission features. We select a 8′′ × 8′′ square region north-east of the main arc where there are no galaxies or foreground stars. In each narrow band map, we compute the standard deviation in surface brightness within this square and use it as the average background surface brightness noise level. The 1σ background surface brightness levels for the different narrow band maps are summarized in Table 2. We use these background surface brightness levels to quantify statistically significant emission in the rest of the paper.

### 3.3. Source Plane Reconstruction

All the 2D images from the data cube are in the image plane. To reconstruct the source plane maps for Mg II, we use the software package LENSTOOL 2 (Kneib et al. 1996; Jullo et al. 2007; Jullo & Kneib 2009) using the lensing model from Sharon et al. (2012); Lopez et al. (2018). Specifically, we used the direct reconstruction (cleansens task) in LENSTOOL to convert the image plane fluxes to the source plane with ray-tracing provided by our best-fit lensing mass model. We preserve the surface brightness to accurately reconstruct the surface brightness distribution of different images in the source plane. For the highly magnified images 1 and 2, we use the cleansens task of LENSTOOL with a grid over-sampling parameters of \( \text{ech} = 10 \) on the image and \( \text{sech} = 8 \) on the source plane to obtain a source pixel size of 0.025′′ (0.21 kpc). For image 3 and the counter arc, we choose a sub-sampling parameters of \( \text{ech} = 5 \) on the image and \( \text{sech} = 3 \) on the source plane to create the reconstructions. This resulted in a pixel size of 0.067′′ (0.56 kpc) in the source plane. We also propagate the uncertainties on the lens model to all our measured distances and areas in the source plane.

The typical atmospheric seeing at the time of the observation was 0.8′′. This corresponds to 4 spatial pixels in the image plane based on MUSE spatial resolution. We express it analytically as a 2D normalized Gaussian with a FWHM = 0.8′′ or 4 pixels in the image plane. To account for the effects of the seeing in the source plane,

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**Table 1.** Absorption and emission lines used in this work.

| Transition | \( \lambda \) | Type       |
|------------|-------------|------------|
| Mg II      | 2796.351    | Resonant abs/ems |
|            | 2803.528    | Resonant abs/ems |
| Fe II*     | 2365.552    | Fine-structure ems |
|            | 2396.355    | Fine-structure ems |
|            | 2612.654    | Fine-structure ems |
|            | 2626.451    | Fine-structure ems |
|            | 2632.108    | Fine-structure ems |
| [O II]     | 2470.97     | Nebular Emission |
|            | 2471.09     | Nebular Emission |

\( ^a \) Atomic data from Morton (2003) and Leitherer et al. (2011)

\( ^b \) Vacuum wavelength in Å.

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**Table 2.** 1σ Surface brightness background level for each map in units of \( 10^{-17} \, \text{erg} \, \text{s}^{-1} \, \text{cm}^{-2} \, \text{arcsec}^{-2} \).

| Transition | E+C | C | RE | \( \Delta \lambda \) [Å] |
|------------|-----|---|----|----------------------|
| Full Mg II | 2.99| 1.63| 2.86| 39                   |
| Mg II 2803 Primary | 0.296 | 0.608 | 0.743 | 10                  |
| Mg II 2803 Secondary | 0.231 | 0.22 | 0.372 | 6                    |
| Fe II* | 5.15 | 5.58 | 7.45 | 133               |
| [O II] | 0.237 | 0.258 | 0.285 | 14                |

\( ^a \) Emission+Continuum.

\( ^b \) Continuum.

\( ^c \) Residual Emission.

\( ^d \) Width of each wavelength window in Å.

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2 http://projects.lam.fr/projects/lenstool
Figure 2. Mean 1D spectrum of the RCSGA032727-132609 main arc centered on the Fe II* and [O II] lines. The solid black line represents the flux and the solid cyan line represents the corresponding uncertainty on the flux. The shaded boxes show the wavelength windows used to create the Fe II* emission (faint blue), [O II] emission (faint green), and local stellar continuum (faint red and faint orange) maps, respectively. The width of the stellar continuum windows is equal to the width of the Fe II* and [O II] emission wavelength windows, respectively.

Figure 3. Mean 1D spectrum of the main arc containing the Mg II doublet. The solid black line shows the flux and the solid cyan line shows the error on the flux. Left: The faint blue regions represent the selected wavelength window around the Mg II emission lines. The faint red regions represent the selected wavelength window for the corresponding continuum region. Right: The selection of the wavelength windows for the primary and secondary emission peaks of the Mg II 2803 emission line. The faint blue and faint red regions represent the emission and continuum windows for the primary peak, respectively. The faint green and faint yellow regions represent the emission and continuum windows for the secondary peak, respectively.
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we inject a 2D Gaussian at the central regions of images 1, 2, 3, and the counter arc in the image plane. We then reconstruct that 2D Gaussian in the source plane to account for atmospheric seeing in our observations. These reconstructions are shown as filled yellow ellipses in all source-plane images.

3.4. Radial Profiles

To quantify the spatial extent of the galactic outflow, we need to constrain the Mg II surface brightness radial profile, which traces the entrained outflowing Mg II gas illuminated by back-scattered radiation (Prochaska et al. 2011).

We first reconstruct all the image-plane emission maps in the source plane of the galaxy. For each image, we select the pixel with the maximum surface brightness as the center. We compute the mean surface brightness profile in the source plane as a function of physical distance with the center defined above. We use jackknife re-sampling from astropy (Astropy Collaboration et al. 2013, 2018) to quantify the uncertainty in mean surface brightness of each radial bin. In short— in each radial bin a pixel is randomly excluded and randomly replaced with one of the remaining pixels. We compute the mean surface brightness and repeat the step until each pixel has been excluded once at least. The 16th and 84th percentile of the final mean surface brightness distribution gives us the 1σ uncertainty of mean surface brightness in each radial bin.

3.5. Mg II Covering Fraction

Using the source-plane reconstructed Mg II emission maps, we constrain the observed spatial incidence of the Mg II emitting region around a galaxy. We quantify this as the Mg II emission covering fraction $C_f(r)$:

$$C_f(r) = \frac{N_{(3\sigma)}(r)}{N_{\text{total}}(r)},$$

where $N_{(3\sigma)}(r)$ is the number of pixels within a radial bin, that are detected at higher than $3\sigma$ significance relative to the background, and $N_{\text{total}}(r)$ is the total number of pixels in the same bin. We use the Wilson score interval$^3$ to constrain the confidence intervals of $C_f(r)$. $C_f(r)$ effectively quantifies the fraction of the total area around the galaxy within a radial bin, where Mg II emission is detected.

4. RESULTS

In the following sections we present the spatial extent of Fe II$^*$, [O II], and Mg II emission detected around RCSGA032727-132609 and quantify the Mg II spatial extent and covering fraction as a function of galactocentric radius.

4.1. Nebular Emission

We first study the spatial extent of the nebular [O II] emission traced by the emission doublet at $\lambda\lambda$ 2470.79, 2471.09Å. We create an emission map around the doublet as described in Section 3. We present the [O II] emission+continuum maps for the counter arc in the image plane in the left panel of Figure 4. The 10σ surface brightness contours for the [O II] emission (magenta contours) and stellar continuum (black contours) are coincident with each other in almost all regions. This clearly shows that the [O II] emission is mostly confined within the projected stellar continuum region of the galaxy. This suggests that in this galaxy [O II] emission is not spatially extended relative to the stellar continuum. This is in contrast to what is seen in Rupke et al. (2019), where the [O II] emission doublet $\lambda\lambda$ 3726, 3729 Å could be seen extending out to 100 kpc from a low-z ($z \sim 0.5$) star-bursting galaxy.

4.2. Fe II$^*$ Emission

We further study the spatial extent of the prominent Fe II$^*$ fluorescent or non-resonant emission (see Figure 2). Fe II$^*$ fluorescent emission in outflowing gas arises owing to the de-excitation of the resonant Fe II absorption lines. The photons are re-emitted at different wavelengths than those of the absorption lines. This happens because the electrons move from the excited state to one of the ground state levels close to the original ground state level but with slightly different energy due to the fine-structure splitting of the ground state (Prochaska et al. 2011). To maximize the SNR, we construct one combined Fe II$^*$ emission map by combining five narrow emission regions traced by Fe II$^*$ emission lines at $\lambda\lambda$ 2365Å, 2396Å, 2612Å, 2626Å, and 2632 Å as described in Section 3.2.

Figure 4, right panel shows the Fe II$^*$ emission + continuum maps for the counter arc in the image plane. The 10σ surface brightness contours for the Fe II$^*$ emission and stellar continuum are similar in almost all regions. These contours are also almost matching in the source plane (not shown here). This provides strong evidence that the Fe II$^*$ fine-structure emission is not spatially extended compared to the stellar continuum in this galaxy. As Fe II$^*$ fine-structure emission lines may trace the most dense regions of the outflowing gas (Prochaska et al. 2011), our results suggest that the most dense part of the outflowing gas may reside relatively close to the star-forming regions of this galaxy.

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$^3$ https://github.com/rongmon/rbcodes/
Here, we investigate the spatial extent of the MgII emission doublet around this galaxy. We construct the MgII emission and residual emission maps as described in Section 3.2.

4.3.1. Mg II Emission in the image plane

To maximize the SNR, we first create the integrated MgII emission maps by summing both the 2796 Å and 2803 Å emission doublets together (see Figure 3). We refer to them as Full MgII emission maps. Figure 5 shows the image plane maps of MgII emission+continuum and MgII residual emission for the main arc (top panels) and the counter arc (bottom panels), respectively. Figure 5, left panels show the 10σ surface brightness contours for MgII emission+continuum (magenta line) and the stellar continuum (black line), respectively. It can be clearly seen that MgII emission is more spatially extended relative to the stellar continuum for both the main arc and the counter arc. The right panels show the MgII residual emission observed around the main arc and the counter arc. The white contours represent 3σ surface brightness level of residual emission. In the main arc (top right panel), MgII residual emission in the image plane is mostly extended around image 3 and region U, and has the least spatial extent around region B. MgII residual emission is also spatially extended around the less magnified counter arc. In all cases, the MgII residual emission extends beyond the stellar continuum in the image plane.

4.3.2. Mg II Emission in the source plane

To quantify the spatial extent of the MgII emission, we transform the narrow band images into the source plane of the galaxy. We first reconstruct the MgII emission and residual maps around the counter arc as described in Section 3.3. As the counter arc represents the entire galaxy in the image plane, the source plane...
reconstructed image covers the full spatial extent of the galaxy. Figure 7, left panel shows the reconstructed Mg II emission map in the galaxy’s source-plane. The magenta and black contours represent the 10σ (solid lines) and 5σ (dashed lines) surface brightness contours for Mg II emission+continuum and stellar-continuum only, respectively. Clearly, the Mg II emission is significantly spatially extended. Figure 7, middle panel shows the residual Mg II emission map in the source plane. The white contours represent the 3σ residual surface brightness emission. Mg II residual emission is clearly asymmetric and shows small-scale structure. Individual, bright residual emission knots are detected between 10-20 kpc from the center of the galaxy at different incidence. Further, the total observed projected area covered by outflowing gas is $184^{+5}_{-19} \text{kpc}^2$. We compute this area by computing the total area of all pixels exhibiting $> 3\sigma$ residual emission. We are sampling 100 realizations of the lens model to quantify the uncertainties on the measured area. The total observed area of the entire counter arc stamp in Figure 7 up to radial distance of 30 kpc is $1387^{+43}_{-38} \text{kpc}^2$. This exercise clearly demonstrates the clumpy nature of the outflow. We estimate that $13.2^{+0.8}_{-0.7} \%$ of the area of the field of view in Figure 7 shows statistically significant residual Mg II emission.

The residual Mg II emission is clearly spatially asymmetric in Figure 7, middle panel. The surface brightness profile is more extended along the declination direction ($\Delta \delta$ or $\Delta y = 38.9^{+0.8}_{-0.6} \text{kpc}$) than along the right ascension direction ($\Delta \alpha$ or $\Delta x = 30.5^{+0.6}_{-0.6} \text{kpc}$), exhibiting $\sim 27.6^{+0.8}_{-0.7} \%$ more extent along the y-direction than along the x-direction. We measure the spatial extent as the maximum separation between significant residual Mg II emission boundary contours.

However, as lensing magnification is different along each axis, it results in shearing the effect of the seeing in the source plane. So instead of a round smear owing to seeing as one expects in the the image plane, one needs to account for an elliptical smear in the source-plane (yellow ellipse in Figure 7). Both the effect of

Figure 5. Mg II emission maps around the main arc (top row) and the counter arc (bottom row). **Left column:** Mg II narrow-band image for the integrated Mg II doublet. The contours correspond to 10σ surface brightness levels (Table 2) for both the Mg II emission (magenta) and continuum (black), respectively. **Right column:** Mg II continuum-subtracted emission with 3σ surface brightness contour level (white contour, Table 2). Mg II emission is evidently spatially extended relative to the continuum in both the images. The yellow circles in the top left of each subplot represent the typical seeing during observation.
seeing and the effect of this shear need to be accounted for to ascertain the true spatial asymmetry in the Mg II residual emission. To account for this effect on the measured spatial extent in both α and δ directions, we perform a suite of simulations. We inject a series of 2D Gaussians, each with FWHMs ranging from 4 pixels to 50 pixels (pixel physical size = 0.56 kpc), in the source plane at the counter arc location. We then convolve them with the reconstructed seeing in the source plane at the location of the counter arc. We measure the observed x-extent and y-extent after the convolution. This allows us to constrain the impact of seeing in the source plane of the counter arc, as any variation from the circular shape of the injected 2D Gaussian is due to seeing and lensing shear. This effect is very evident for a 2D Gaussian with small FWHM (~ 4 pixels) and is almost negligible at FWHM of 50 pixels. Using these simulations, we can correct our measurements for any asymmetry owing to atmospheric seeing and lensing shear. We invert the relationship between the observed x and y extents of the simulated images, and compute the true size of the structure for any observed x or y extent. The new seeing+lensing shear corrected distances for the Mg II residual emission in the counter arc are Δδ or Δy = 30.0^{+0.7}_{-0.5} kpc and Δα or Δx = 24.8^{+0.5}_{-0.5} kpc, respectively. Even after correcting for atmospheric seeing and lensing shear, the residual Mg II emission is spatially more extended along the declination direction by 20.9^{+0.7}_{-0.6} % (See Table 3).

The residual Mg II emission has some extended shell like structure at ~ -5 and 10 kpc in the Δx direction (Figure 7, middle panel). These shells could be associated with the spiral arm of the galaxy itself. To test that hypothesis, we extract three light weighted spectra: One for the left shell, one for right shell, and one for the middle core. For these three regions, we compute the systemic redshift by using the [O II] emission line and compute the kinematics of the Mg II emission components. The detailed models will be described in a future paper (Shaban et al. 2021 in preparation) but the resultant Mg II emission velocities are almost identical within error bars for all three regions, whereas the systemic redshifts are varying. This rules out the possibility that these structures are associated with the spiral arms of the galaxy, and are indeed gas structures only traced by Mg II emission. This is also seen qualitatively in Figure 7, right panel. The source-plane reconstructed HST image traces the stars of the galaxy, which is spatially offset from the location of the Mg II emitting regions.

In Figure 8, we present the source plane reconstruction of the counter arc showing the full Mg II doublet emission (left panel), Mg II 2803 primary (middle panel) and Mg II 2803 secondary (right panel) components, respectively. The Mg II 2803 primary and secondary components are kinematically separated by Δv ≈ 400 km s^{-1} and the secondary component is detected in almost all regions of the galaxy except in region U. In the source plane, we detect a significant residual Mg II emission (> 3σ) for both the primary and secondary Mg II 2803 Å emission peaks. The two components have similar projected spatial extent but are asymmetric (Figure 8). The Mg II 2803 Å primary surface brightness profile is more extended along the declination direction by ≈ 8.1 kpc (≈2.5 kpc after seeing+lensing shear correction). The

![Figure 6. Mg II emission maps (in the counter arc) for Mg II 2803 primary emission component (Left panel) and secondary emission component (Right panel), respectively. The contours correspond to 10σ surface brightness levels. The magenta contours are for Mg II emission+continuum and the black contours are for the stellar continuum. Both the primary and secondary Mg II emission peaks are spatially extended relative to the stellar continuum. The yellow circles in the top left of each subplot represent the typical seeing during observation.](image-url)
observed Mg II 2803 Å secondary residual profile shape is slightly elongated along the declination direction by \( \approx 2.4 \) kpc. After correcting for the seeing+lensing shear, the Mg II 2803 Å secondary residual emission becomes more extended along the right ascension direction by \( \approx 2.5 \) kpc. The measured distances for the two components before and after correcting for seeing+lensing shear are summarized in Table 3. As they are kinematically distinct, they may exist in different physical regions along the line of sight. This can be interpreted as the bulk of the two Mg II emitting components being at different velocities. There may be some kinematic overlap between the two components as they appear partially blended in the 1D spectrum (Figure 3). Their kinematic offset combined with different morphology of the two emission lines suggest that they may have different origin (e.g., different star-bursts, or originating from different star-forming regions), although they appear approximately co-spatial in projection. Further analysis of the absorption lines will provide more insight regarding the line of sight geometry of the outflow.

4.3.3. Mg II Emission Radial Profiles

We characterize the azimuthally averaged surface brightness profile as a mean 1D Mg II radial emission profile in Figure 9. We define the center of the radial profile as the the brightest pixel of the Mg II residual emission at the counter arc in the source plane. In each radial bin, we compute the mean surface brightness of all pixels above 3\( \sigma \) background level, shown as filled green squares. If no pixels in that bin are above the 3\( \sigma \) background level, we report the 2\( \sigma \) background surface brightness level as non-detection (open squares). Patchy Mg II emission can be detected out to an observed radial distance of \( 26.5^{+0.5}_{-0.4} \) kpc. For comparison, the dashed golden line shows the typical seeing as present in the reconstructed source-plane. Clearly most of the residual Mg II emission is spatially extended.

As gravitational lensing allows us to zoom-in on smaller regions around the highly magnified image of the main arc (Figure 1), we can probe if Mg II emission is spatially extended around individual star-forming regions within the galaxy. We use images 1, 2, and 3 (Figure 1) to trace the Mg II emission similar to what is done for the counter arc. Figure 10 shows the reconstructed Mg II emission maps in the source plane for the three images. While Figure 10 spatially resolves many of the bright star-forming regions, regions E and B are blended in image 1 (left column). Image 2 has the highest spatial resolution in the source plane as it is highly magnified compared to the other images, such that the regions U, E, and B are spatially resolved (middle panel). Region G is found in image 3 (right column). From all the source-plane reconstructed images, we qualitatively find that the Mg II emission contours extend beyond the continuum at the 3\( \sigma \) significance level. The Mg II residual emission (Figure 10, bottom panels) is significantly extended spatially, with emission arising both in the bright star-forming clusters (e.g., E, B, and U) as well as a diffuse spatially extended component.

We extract the mean surface brightness radial profiles for Mg II emission, continuum, and residual emission as described in 3.4. We do not show the radial profiles for [O II] and Fe II* because they are not spatially extended. Figure 11 shows these radial profiles for these regions as filled black, yellow and green points. Figure 11 shows that the Mg II residual emission extends to \( \approx 6.0^{+0.2}_{-0.2} \) kpc, \( 7.0^{+0.3}_{-0.2} \) kpc, and \( 8.5^{+0.1}_{-0.1} \) kpc in regions E, U, and B, respectively, as measured from the brightest central pixel of each individual region. The residual Mg II emission in image 3 extends radially up to \( 29.7^{+1.6}_{-1.6} \) kpc. We find that the 3\( \sigma \) radial extents of residual emission is more than 25 kpc for both image 3 and the counter arc. Image 3 and the counter arc provide the extent of the residual emission in the galaxy as a whole. However, image 3 is much more magnified and distorted compared to the counter arc. Furthermore, image 3 has some contribution from two foreground cluster galaxies (See Figure 1 in Wuyts et al. (2014)). So, the counter arc provides a more reliable measure for the radial extent of the outflow. We parametrize the Mg II emission and residual surface brightness radial profiles with an exponential for the inner region of the profile plus a power law for the outer region as follows:

\[
I(r) = I_{0.1} e^{-\left(\frac{r}{r_0}\right)} + I_{0.2} \left(\frac{r}{r_b}\right)^\beta
\]

where \( I_{0.1} \) is the surface brightness intensity at \( r = 0 \), \( r_0 \) is a scale radius for the exponential, \( I_{0.2} \) is the surface brightness intensity at \( r = r_b \), \( r_b \) is the characteristic radius for the power law, and \( \beta \) is the index of the power law. All these parameters are free to vary during the fitting process. Then, we convolve equation 4 with the corresponding reconstructed seeing for each region in the source plane. We fit this convolved model using the Markov chain Monte Carlo (MCMC) sampling using the python package EMCEE \(^4\) (Foreman-Mackey et al. 2013). The best fitting parameters using the model described here are summarized in Table A1.

4.4. Covering fraction

\(^4\) https://emcee.readthedocs.io/
The covering fraction in this work represents the fraction of area around the galaxy which is covered by the cool entrained outflowing gas (in radial bins), traced by the Mg II residual emission above the 3σ limit (see Section 3.5 for details). We choose the brightest pixel of the reconstructed residual counter arc as the center (Figure 7, middle panel). We compute the fraction of pixels in each radial bin that are above the 3σ limit out to 30 kpc. We select this distance limit to avoid any contributions from other bright foreground objects near the counter arc. The covering fraction can be interpreted as a measure of the porosity or patchiness of the outflowing gas (Martin & Bouché 2009; Chisholm et al. 2016b, 2018). In this work, we use a different approach to measure $C_f(r)$. We measure the total area (pixels) exhibiting statistically significant Mg II emission to calculate $C_f(r)$. We calculate $C_f(r)$ in the source plane reconstructed counter arc only because it represents the full galaxy. Figure 12 shows the measured covering fraction as a function of radial distance for the Mg II emission doublet, continuum and Mg II residual emission, respectively. For the Mg II residual emission, we see that $C_f$ is nearly unity in the inner 3 kpc, which means that outflowing gas is ubiquitous at these inner radii. As we go outward from 3 kpc to 10 kpc, the covering fraction drops to $\sim 20\%$. From 10 kpc to 30 kpc, it gradually decreases and oscillates between 0 - and 10 %. These fluctuations indicate that the outflowing gas is not uniformly distributed and is patchy. There are regions, where larger concentrations of outflowing gas exist even at large radial distances, and there are regions where little outflowing gas is detected. This reaffirms the canonical picture of a large-scale patchy galactic outflow that is being traced by the Mg II emitting gas. We characterize the Mg II residual emission covering fraction radial profile using a power law:

$$C_f(r) = C_{f,0} \left( \frac{r}{1\text{kpc}} \right)^\gamma$$

where $C_{f,0}$ is the covering fraction at the center of the galaxy, and $\gamma$ is the power law index. We convolve this

Table 3. Maximum spatial extent of Mg II residual emission

| Transition/Component | Observed $\Delta x$ [kpc] | Observed $\Delta y$ [kpc] | Corrected $\Delta x$ [kpc]$^a$ | Corrected $\Delta y$ [kpc]$^a$ |
|----------------------|---------------------------|---------------------------|-------------------------------|-------------------------------|
| Full Mg II Emission  | $30.5_{-0.6}^{+0.6}$     | $38.9_{-0.6}^{+0.8}$     | $24.8_{-0.5}^{+0.5}$          | $30.0_{-0.5}^{+0.7}$          |
| Primary Mg II 2803 Å Component | $8.9_{-0.2}^{+0.2}$     | $17.0_{-0.2}^{+0.3}$     | $6.4_{-0.1}^{+0.1}$           | $8.9_{-0.2}^{+0.3}$           |
| Secondary Mg II 2803 Å Component | $13.7_{-0.3}^{+0.3}$     | $16.1_{-0.2}^{+0.3}$     | $10.5_{-0.2}^{+0.2}$          | $8.0_{-0.3}^{+0.2}$           |

$^a$ After seeing and lensing shear correction (see Section 4.3.2)
Figure 8. Source plane surface brightness maps of the counter arc for the Mg II full residual emission (left panel), the primary 2803 Å emission peak (middle right), and the secondary emission peak (right panel). The white contours are the 3σ residual surface brightness level for each map. The golden bar denotes 5 kpc in the source plane. The yellow ellipse in the top right of each subplot represents the typical seeing in the source plane for the counter arc.

Figure 9. Mean Mg II residual emission surface brightness radial profiles for the full Mg II emission window in the counter arc in source plane. In each radial bin the mean surface brightness of statistically significant (> 3σ) residual emission is shown (green filled squares). In radial bins without any statistically significant residual emission, 2σ surface brightness upper limits (open squares) are presented. The dashed gold line represents the seeing for the counter arc in the source plane.

power law with the seeing of the counter arc in the source plane. We obtain a best fit model with $\gamma = -1.25^{+0.02}_{-0.02}$. This model is shown as a green dotted line in Figure 12. This Figure also shows that the model convolved with the seeing (green dashed line) is a better characterization of the Mg II covering fraction. We constrain the total area covered by the residual emission tracing the outflow and the total area enclosed within 30 kpc.

By dividing the outflow area $A_{\text{out}}$ by the total area $A_{\text{tot}}$ of the counter arc stamp, we can get an average value for the covering fraction. The measured value for the average covering fraction is $C_f = A_{\text{out}} / A_{\text{tot}} = 0.13^{+0.01}_{-0.01}$. The covering fraction beyond the stellar continuum is an indicator of the morphology and patchiness of the outflowing gas. In other words, it quantifies the fraction of the projected area around a galaxy where outflowing gas can be detected (Chisholm et al. 2016b). Several studies quantified the gas covering fraction using partial covering of blueshifted absorption lines, with some assumption about the relation between the velocity and radius (e.g., Chisholm et al. 2016b, 2018). Typically these works find a decreasing $C_f$ with distance characterized by a power-law. Our measurement of the $C_f$ power law is comparable to these studies, even though a completely different approach is being used here. Additional analysis of these two methods are needed to compare if the Mg II emission traced gas covering fraction, and the absorption traced line-of-sight covering fraction are indeed probing the same gas covering fraction. This will be done in RCSGA032727-132609 as a part of a future paper (Shaban et al. in prep). Covering fraction is one of the important quantities in the calculation of the mass outflow rate $\dot{M}_{\text{out}}$. Most studies assume $C_f$ to be constant. Our measurements conclusively show that the outflow gas covering fraction changes as we move outward from the central region of the galaxy. These constraints will enable robust mass outflow rates for this system.

5. DISCUSSION AND CONCLUSIONS
Figure 10. Source plane reconstruction of Mg II emission doublet $\lambda\lambda$ 2796, 2803 Å surface brightness maps in images 1 (left column), 2 (middle column) and 3 (right column), respectively. Top panels: Surface brightness maps of the Mg II doublet 5σ (dashed lines) and 10 σ (solid lines) surface brightness contours for Mg II emission (magenta lines) and the corresponding stellar-continuum (black lines) are shown. We label the four individual star-forming regions as shown in Figure 1. Bottom panels: Mg II residual surface brightness emission (continuum-subtracted emission). 3σ residual surface brightness contours are shown (white lines). The reconstructed typical seeing is shown as filled yellow region in the left corner of each subplot.

In this paper we present observations of [O II], Fe II, and Mg II emission lines in RCSGA032727-132609, a $z \approx 1.7$ galaxy, lensed by a foreground galaxy cluster at $z \approx 0.56$. Lensing distorts light coming from the background galaxy that results in multiple images of the source galaxy RCSGA032727-132609 at the plane of the cluster, referred to as the “image plane”. Some of these images are highly magnified and represent small star-forming regions within the galaxy (e.g. images 1 and 2 in Figure 1). Other images are less magnified and represent the full extent of the galaxy (e.g. image 3 and the counter arc in Figure 1). With VLT/MUSE observations of these different images, we study the spatial extent of the emission lines tracing galactic outflows, and provide strong constraints on the spatial extent of the outflowing gas. Our main results are:

- We observe and compare the [O II] nebular emission with the stellar continuum emission around the galaxy. The [O II] nebular emission is not spatially extended compared to the stellar continuum, as expected for such lines (Figure 4).

- We detect several Fe II fine structure emission lines. Compared to the stellar continuum, the Fe II fine structure emission is not spatially extended but it closely traces the stellar continuum emission (Figures 2 & 4).

- The Mg II resonant emission lines $\lambda\lambda$ 2796, 2803 Å are spatially extended in all regions in the image-plane and the source-plane. From the surface brightness radial profiles, we detect a patchy Mg II residual emission in the whole galaxy out to an average radial distance of $26.5^{+0.5}_{-0.4}$ kpc (with a maximum extent of $\Delta \delta = 38.9^{+0.8}_{-0.6}$ kpc) (Figures 7 & 9).

- After correcting for seeing and lensing shear, residual Mg II emission profile is asymmetric and $20.9^{+0.7}_{-0.6}$% more extended along the declination compared to the right ascension ($\Delta \delta$ or $\Delta y = 30.0^{+0.7}_{-0.5}$ kpc, and $\Delta \alpha$ or $\Delta x = 24.8^{+0.5}_{-0.3}$ kpc; Figure 7).

- We detect two distinct redshifted emission peaks at different velocities ($\Delta v \approx 400$ km s$^{-1}$) for the Mg II 2803 Å emission line. The Mg II emission
corresponding to these peaks is also spatially extended similar to the full Mg II emission profile. The observed primary emission component is more extended along the declination direction by \( \approx 8.1 \) kpc (\( \approx 2.5 \) kpc after seeing+shear correction). While the observed secondary emission component is more extended along the declination by \( \approx 2.4 \) kpc. After correcting for the seeing+ lensing shear, the secondary component shows more extent along the right ascension direction by \( \approx 2.5 \) kpc (Figure 6 & Table 3). This is an evidence for the complex, inhomogenous, and asymmetric nature of the geometry of galactic outflows.

- The kinematic offset (\( \Delta v \approx 400 \text{ km s}^{-1} \)) and different morphology of the two Mg II 2803 Å emission components suggest that these two emission peaks may be tracing two different parts of the outflowing gas. The outflowing gas may have different origin (e.g. different discrete star-bursts, or originating from different star-forming regions), although they appear approximately co-spatial in projection (Figure 8).

- We detect the residual Mg II emission in the different images of star-forming regions. Image 3 (tracing almost the whole galaxy) shows a radial extent of \( 29.7_{-1.4}^{+1.6} \) kpc. The radial extent of the residual emission is \( 6.0_{-0.2}^{+0.3} \) kpc, \( 7.0_{-0.3}^{+0.3} \) kpc, and \( 8.5_{-0.1}^{+0.1} \) kpc at the 3\( \sigma \) significance for regions E, U, and B, respectively (Figures 10 & 11). This shows that individual star forming regions either started the outflows at different times or they ejected the outflows at different velocities.

- We quantify the spatial covering fraction of the residual Mg II emission \( C_f(r) \), the fraction of area on the sky (pixels) covered by significant Mg II residual emission. We find that \( C_f(r) \) is unity at \( r < 3 \) kpc, but rapidly falls off to \( \sim 10\% \) at 20 kpc, with an excess of \( C_f \sim 0.5 \) at 9 kpc. This suggests a non-uniform and clumpy morphology of the outflowing gas. We characterize \( C_f(r) \) with power law convolved with the seeing with index \( \gamma = -1.25_{-0.02}^{+0.02} \). We quantify that the average Mg II residual \( \langle C_f \rangle \) is \( 0.13_{-0.03}^{+0.03} \) deduced from the area of the outflow, within \( r=30 \) kpc (Figure 12).

The spatially non-extended nature of the fine-structure Fe II* emission in this galaxy suggests that Fe II* emission may not trace the optically thin parts of the galactic outflows. This is likely because the Fe II* is arising from fluorescence powered by resonant Fe II absorption (Prochaska et al. 2011). Thus, the bulk of the Fe II*
emission comes from the densest part of the outflow at the core region of the galaxy, and is not spatially scattered at large distances. Using a galaxy sample from the MUSE Hubble Ultra Deep Field Survey, Finley et al. (2017a) reported that low-mass galaxies with $<10^9M_\odot$ exhibit pure Mg II emission that may be tracing the star-forming HII regions (see also Chisholm et al. 2020), whereas high-mass galaxies ($>10^{10}M_\odot$) only exhibit Fe II* fluorescent emission without any Mg II emission and intermediate mass galaxies exhibit both Fe II* and P-Cygni Mg II emission. Finley et al. (2017b) also detected fluorescent Fe II* emission (and no Mg II emission) in a star-forming galaxy at $z = 1.29$ that is 70% more extended than its stellar continuum out to $\sim 4$ kpc. By contrast, RCSGA032727-132609 is a star-forming galaxy with $M_*=6.3 \pm 0.7 \times 10^9M_\odot$ (Wuyts et al. 2012). We detect both Fe II* and Mg II emission lines in our spectra and find that Fe II* emission around this galaxy is not spatially extended compared to its stellar continuum. However, the Mg II emission around RCSGA032727-132609 is significantly extended spatially.

Our main finding shows that Mg II emission halo around RCSGA032727-132609 has a size of $\sim 30$ kpc. Although this emission is spatially extended for multiple different regions, the Mg II surface brightness profiles measured around individual star-forming regions of the galaxy are not uniform (Section 4.3.2). These variations are significant as they suggest that the outflowing gas traced by the Mg II emission is powered by the local star-forming regions in the host galaxy. Figure 7 shows distinct structure in Mg II residual emission which strongly points towards a clumpy asymmetric outflow being driven from this galaxy. Together, these two pieces of evidence suggest that the properties of individual star-forming regions may determine how far outflowing gas can be driven from a galaxy (Bordoloi et al. 2016). We will explore this hypothesis in a follow up paper that will study the kinematics of the outflowing gas in this galaxy in detail (Shaban et al. in prep).

Recently, new evidence has increasingly shown spatially extended emission owing to galactic outflows at different cosmic epochs. Chen et al. (2021) reported spatially extended $Ly\alpha$ emission around a group of three lensed galaxies at $z = 3.038$ out to $\sim 30$ kpc. Zabl et al. (2021) measured Mg II extended emission around a galaxy at $z = 0.702$ up to $\approx 25$ kpc. One of the most extreme cases of spatially extended outflow was reported by Rupke et al. (2019), who measured an outflow up to 100 kpc in a star-burst galaxy called ‘Makari’ at redshift $\sim 0.47$ using [O II] emission. Recently, Burchett et al. (2021) found that the Mg II residual emission around a star-forming galaxy TKRS4389 ($z = 0.6942$) extends out to a diameter of 31 kpc. Our findings of spatially extended Mg II emission around RCSGA032727-132609 to a maximum spatial extent of $\approx 39.0^{+0.8}_{-0.6}$ kpc is comparable to these studies. Most of these studies (particularly with Mg II emission) have been at $z < 1$. Our finding is the highest redshift detection of spatially extended galactic wind traced by Mg II emission ($z \sim 1.7$). Further, while most other studies have targeted unlensed galaxies to trace the global Mg II spatial extent, RCSGA032727-132609 is strongly gravitationally lensed, magnifying the Mg II emission in individual star-forming regions. This enables us to measure the spatial extent of the outflowing gas not only around the galaxy as a whole but also around individual star forming regions of the galaxy at $z \sim 1.7$.

Recent theoretical works have also reported how the CGM of galaxies will look in Mg II emission. Nelson et al. (2021) reprocessed the TNG50 simulations to study the Mg II halos in the CGM of galaxies within redshift range $0.3 < z < 2$ and stellar mass range $7.5 < \log(M_*/M_\odot) < 11$. They assumed that Mg II emission is optically thin and they neglect the impact of resonant scattering. They found out that the Mg II halos around the galaxies are ubiquitous in star-forming galaxies regardless of the redshift or the stellar mass. One of the origins of these halos is galactic outflows with complex morphology. The measured covering fraction radial profile for RCSGA032727-132609 in this work is an indicator of the morphology and complexity of the outflow. It shows a variation in the morphology of the Mg II residual emission tracing the outflow. This is consistent with this simulation’s results.

Our approach, that combines the power of IFUs and strong gravitational lensing is a powerful and promising way to study galactic outflows at high redshifts, given that a well defined lens model exists. In the near future, by increasing the sample size, we aim to build up a robust and statistically significant sample of spatially resolved measurements of galactic outflows, that will significantly enhance our understanding of the morphology and spatial extent of the outflows at cosmic noon.

This work is based on observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere under ESO program 098.A-0459(A). In addition, we used observations made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Science Institute (STScI). STScI is operated by the Association of Universities for Research in Astronomy, Inc. under
Table A1. The parameters for the Mg II radial profiles models. The units for $I_{O,1}$ and $I_{O,2}$ are erg s$^{-1}$ cm$^{-2}$ arcseconds$^{-2}$.

| Profile                  | $I_{O,1}[10^{-15}]$ | $I_{O,2}[10^{-15}]$ | $r_0$ [kpc] | $r_0$ [kpc] | $\beta$  |
|--------------------------|---------------------|---------------------|-------------|-------------|----------|
| Counter Arc Emission+Continuum | 1.76$\pm$0.03      | 0.13$\pm$0.02      | 2.12$\pm$0.06 | 6.39$\pm$4.33 | $-0.35^{+0.04}_{-0.04}$ |
| Counter Arc Emission     | 1.34$\pm$0.02      | 0.06$\pm$0.02      | 2.3$\pm$0.07  | 10.06$\pm$5.11 | $-0.12^{+0.08}_{-0.08}$ |
| Counter Arc Residual Emission | 0.41$\pm$0.02      | 0.12$\pm$0.01      | 1.89$^{+0.18}_{-0.19}$ | 0.7$^{+0.16}_{-0.15}$ | $-0.16^{+0.02}_{-0.02}$ |
| Image 3 Emission+Continuum | 3.35$\pm$0.05      | 0.27$\pm$0.04      | 1.64$^{+0.07}_{-0.07}$ | 5.31$^{+2.97}_{-1.74}$ | $-0.35^{+0.03}_{-0.03}$ |
| Image 3 Continuum        | 2.77$\pm$0.05      | 0.15$\pm$0.02      | 1.71$^{+0.08}_{-0.08}$ | 9.13$^{+7.14}_{-4.89}$ | $-0.14^{+0.05}_{-0.05}$ |
| Image 3 Residual Emission | 0.58$\pm$0.01      | 0.12$\pm$0.02      | 1.77$^{+0.09}_{-0.09}$ | 5.85$^{+3.99}_{-2.08}$ | $-0.4^{+0.03}_{-0.03}$ |
| Knot E Emission+Continuum | 1.52$\pm$0.06      | 0.19$^{+0.02}_{-0.02}$ | 0.95$^{+0.09}_{-0.08}$ | 2.61$^{+0.74}_{-0.43}$ | $-0.51^{+0.06}_{-0.05}$ |
| Knot E Continuum         | 1.19$\pm$0.06      | 0.11$^{+0.04}_{-0.03}$ | 1.11$^{+0.13}_{-0.15}$ | 3.14$^{+2.24}_{-0.87}$ | $-0.58^{+0.13}_{-0.12}$ |
| Knot E Residual Emission | 0.18$\pm$0.02      | 0.1$^{+0.03}_{-0.02}$ | 0.2$^{+2.12}_{-0.08}$ | 4.56$^{+4.19}_{-1.93}$ | $-0.39^{+0.14}_{-0.04}$ |
| Knot B Emission+Continuum | 1.01$\pm$0.03      | 0.08$^{+0.01}_{-0.01}$ | 1.33$^{+0.12}_{-0.12}$ | 8.74$^{+5.42}_{-4.15}$ | $-0.2^{+0.19}_{-0.19}$ |
| Knot B Continuum         | 0.75$\pm$0.02      | 0.06$^{+0.02}_{-0.01}$ | 1.55$^{+0.15}_{-0.15}$ | 5.72$^{+6.29}_{-2.77}$ | $-0.16^{+0.12}_{-0.09}$ |
| Knot B Residual Emission | 0.26$\pm$0.02      | 0.06$^{+0.01}_{-0.01}$ | 0.44$^{+0.17}_{-0.17}$ | 6.18$^{+5.83}_{-3.21}$ | $-0.23^{+0.07}_{-0.06}$ |
| Knot U Emission+Continuum | 1.03$\pm$0.08      | 0.12$^{+0.04}_{-0.04}$ | 1.99$^{+0.18}_{-0.16}$ | 3.14$^{+0.22}_{-0.1}$ | $-0.33^{+0.11}_{-0.16}$ |
| Knot U Continuum         | 0.74$\pm$0.02      | 0.06$^{+0.02}_{-0.01}$ | 1.7$^{+0.19}_{-0.21}$ | 5.11$^{+1.88}_{-1.52}$ | $-0.41^{+0.27}_{-0.25}$ |
| Knot U Residual Emission | 0.3$^{+0.02}_{-0.02}$ | 0.11$^{+0.03}_{-0.02}$ | 0.72$^{+0.03}_{-0.02}$ | 5.39$^{+1.66}_{-1.62}$ | $-0.29^{+0.23}_{-0.14}$ |

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APPENDIX

A. RADIAL PROFILES PARAMETERS

In this appendix we report the best fit parameters of the fitted Mg II radial profiles in Table A1.

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Facilities: MUSE-VLT

Software: Astropy (Astropy Collaboration et al. 2013, 2018), matplotlib (Hunter 2007)
