A spectroscopic study of 14 structures behind Holm15A: Detecting a galaxy group candidate at z=0.58.

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ABSTRACT

Holm15A hosts one of the most massive black holes ever known. Hence, it is important to characterize any structure within its core to avoid any wrong association with its central black hole and, therefore, bias any future study. In this work, we present the first identification and characterization of 14 structures hidden behind the surface brightness of Holm15A. We model and subtract the spectral contribution of Holm15A to obtain the spectral information of these structures. We spectroscopically confirm that the 14 objects found are not associated with Holm15A. Ten objects have a well-defined galaxy spectrum from which we implement a fossil record analysis to reconstruct their past evolution. Nine objects are candidates that support the scenario of mutual crossings. Furthermore, the fossil reconstruction of the group candidates brings evidence that at least three different merger trees could assemble the galaxy group. We characterize the properties of the galaxy group from which we estimate a lower limit of the scale and mass of this group. We obtain a scale of $\sim 146^{+3}_{-3}$ kpc with a dispersion velocity of $622^{+300}_{-200}$ km/s. These estimations consider the lensing effects of the gravitational potential of Holm15A. The other five objects were studied individually. We use public archive data of integral field spectroscopic observations from the Multi-Unit Spectroscopic Explorer instrument.

Key words: galaxies: elliptical and lenticular, cD – galaxies: clusters: general – galaxies: evolution – galaxies: stellar content – gravitational lensing: weak – techniques: imaging spectroscopy

1 INTRODUCTION

Holm15A can be considered one of the most interesting objects in the sky, since its well resolved core structure permits the detailed study of the nature of its supermassive black hole (SMBH). Holm15A is the brightest cluster galaxy (BCG) of Abell 85 (Abell et al. 1989) with a redshift of $z=0.055$ (López-Cruz et al. 2014). Its surface brightness profile has one of the largest cores ever observed that supports the idea that it contains one of the largest SMBHs ever found (López-Cruz et al. 2014; Mehrgan et al. 2019). However, the nature of the SMBH of Holm15A is not completely understood. It is still an open question the existence of a single, a dual or more complex system of SMBHs. Because of this, it is vital to characterize all the observed structures within Holm15A to disentangle the scenario that better describes the nuclear region, particularly, the number of SMBH. In this study, we explore, classify, dissect and analyze a set of 14 observed astronomical objects that were hidden within the surface brightness of Holm 15A.

For this aim, we use integral field spectroscopy (IFS) observations with the Multi-Unit Spectroscopic Explorer (MUSE) instrument. MUSE is located at the Very Large Telescope (VLT) of the European Southern Observatory (ESO, Bacon et al. 2017). The IFS observational techniques spatially resolves the spectral information of an observed target through the use of integral field units (IFU) devices (see the review of Sánchez 2020). With the spatially resolved spectral information, the IFS technique has improved our ability to study the extragalactic physics and spatially dissect the galaxy properties within a global and local view (Ibarra-Medel et al. 2016).

On the other hand, we also use the stellar population synthesis to study the IFS data. The stellar populations synthesis (or archaeological reconstruction) are a strong tool to understanding the galaxy evolution (e.g., Tinsley 1980; Buzzoni 1989; Bruzual & Charlot 2003; Kauffmann et al. 2003a,b; Cid Fernandes et al. 2005; Gallazzi et al. 2005; Tojeiro et al. 2007; Walcher et al. 2011; Goddard et al. 2017). These techniques, also known as the fossil record, model the observed galaxy spectra energy distribution (SED) as the assembly of multiple single stellar populations (SSP) with different ages and metallicities (Conroy 2013). The fossil record method resolves the inverse problem to find the flux contribution of each SSP to the observed spectrum. With this information, it is possible to reconstruct the past evolution of the star formation and enrichment.
of galaxies throughout the cosmic times (Pérez et al. 2013; Camps-Faríná et al. 2022; Zhou et al. 2022). However, the fossil record has the limitation to only access the histories at the sky positions at the observed time (Ibarra-Medel et al. 2019).

With the advent of large IFU surveys and state of the art IFU observations (e.g., Bacon et al. 2001; Cappellari et al. 2011; Croom et al. 2012; Sánchez et al. 2012; Cid Fernandes et al. 2013; Bundy et al. 2015), now it is possible to apply the fossil record method to the resolved spectral information of the galaxies and dissect the galaxy formation through time and space (e.g., Ibarra-Medel et al. 2016; González Delgado et al. 2016, 2017; García-Benito et al. 2017; Ibarra-Medel et al. 2019; Peterken et al. 2020, 2021; Ibarra-Medel et al. 2022). In this point, López-Cruz et al. (2019) applied the stellar population synthesis to disentangle the star formation histories of four galaxy members of the SeyfertâĂŹs Sextet (HCG 79). In that study, they show that it is possible to apply the fossil record to trace the past interactions of galaxy systems by looking into common star formation episodes (Hickson et al. 1992; Plauchu-Frayn et al. 2012; Moura et al. 2020). Hence, the stellar population synthesis is a powerful tool to understand the nature of the galactic systems, uncover their past evolution and demonstrate the past inter-linkage among members of more complex gravitational systems like galaxy groups.

The outline of the paper is arranged as follows. In Section 2, we describe the observational data that where used for this study, and describe the tools used to perform the stellar population synthesis. In Section 3, we explain our spectroscopic analysis, describing the methods and steps to fit the surface brightness of Holm15A. We describe how the spectra of the 14 detected objects where extracted and describe all the steps for the fossil reconstruction. In Section 4, we describe the spectroscopic results of all objects, from which we conclude the existence of a possible galaxy group behind Holm15A. In Section 5, we present a complete characterization of the galaxy group candidate. In Section 6, we give a discussion of the results, and present our conclusions. We have adopted a cosmology with $\Omega_m = 0.27$, $\Omega_k = 0.72$ and $H_0 = 71 \, \text{km s}^{-1} \text{Mpc}^{-1}$.

## 2 DATA AND METHODS

### 2.1 MUSE Data

The MUSE instrument (Bacon et al. 2017) in its Wide Field Mode (WFM) provides a field of view of $59\cdot9 \times 60\cdot0$ with a spatial sampling of $0\cdot2$ per pixel. The average spatial resolution of the MUSE IFS has a full-width at half maximum (FWHM) between $0\cdot3$ to $0\cdot5$. However, in practice, the spatial resolution is limited by seeing. The MUSE spectral range covers the optical region from 4750Å (blue) to 9300Å (red), with spectral resolving power of 1770 (blue) to 3590 (red). For this study, we use the archive data taken with the MUSE WFM of Holm15A with the program ID 099.B-0193 (Mehrgan et al. 2019). The observation was taken on the 16th of November 2017 with the data set ID MUSE.2017-11-16T03:50:01.938. While Mehrgan et al. (2019) measured an FWHM spatial resolution of $0\cdot72$ on the red part of the spectrum, we measured an FWHM of $0\cdot63$ at 7000Å and $0\cdot58$ at 9000Å using the two point sources on the field. We use a Moffat profile (Trujillo et al. 2001) to model the FWHM of the observed seeing within the MUSE database. A detailed description of the seeing modeling is given on Appendix A.

### 2.2 Spectral Fitting

For this work, we use the ryPipe3D code that uses the ryFIT3D pipeline (Lacerda et al. 2022), which is based on the previous Pipe3D/FIT3D code (Sánchez et al. 2016a,b). The workflow of ryPipe3D can be summarized as follows:

a) It extracts an integrated central spectrum to estimate the initial value of the redshift and kinematics.

b) It performs a spatial binning across the FoV of the input datacube to target a signal-to-noise ratio (SNR) of 50 per bin. The SNR is defined within a spectral window that the user can modify (Lacerda et al. 2022).

c) ryFIT3D performs a full stellar population synthesis (SPS) on the coadded spectra within each spatial bin. In this paper, ryFIT3D fits the stellar continuum by using the updated version of the single stellar population (SSP) models of Bruzual & Charlot (2003) (Bruzual et al. 2022 in prep, Sanchez et al. 2022 in prep, Mejía-Narváez et al. 2021) that uses the MaSTAR stellar library (Yan et al. 2019). This library uses a Salpeter (1955) initial mass function (IMF) and it is composed by a grid of $N_A$ ages $\times$ metallicities. In this study, we use three SSP grids, with $N_A = 39$, 36 and 34 ages and have a maximum age of 13.5, 8.5 and 6.25 Gyr due to the observed redshift of our objects (see Section 4). The SSP ages are approximately linearly spaced below 0.02 Gyr and then it is logarithmically spaced (Sanchez et al. 2022 in prep). The SSP metallicities cover the values: $Z_\odot = 0.0001$, 0.0005, 0.0020, 0.0080, 0.0170, 0.0300, 0.0400, with $Z_\odot = 0.019$. For the stellar synthesis, ryFIT3D considers a Cardelli et al. (1989) dust attenuation law.

d) ryPipe3D saves the results of the spectral inversion done by ryFIT3D and reconstructs a set of 2D maps that contains the stellar population properties. During this process, ryPipe3D undone the initial segmentation binning and creates a set of 2D maps that contains the same number of spaxels of the original datacube. For the case of the SPS decomposition, ryPipe3D generates a map of the weights for each SSP per each age and metallicity grid. With these weights, we can reconstruct the star formation histories and the cumulative stellar mass growth across the time (Ibarra-Medel et al. 2016, 2022).

e) Finally, ryPipe3D performs the nebular emission analysis, providing fluxes and kinematic maps of the emission lines (Sanchez et al. 2022 et al. in prep).

In Ibarra-Medel et al. (2019), the Pipe3D code was fully tested using hydro-dynamical cosmological simulations and MaNGA (Bundy et al. 2015) type IFU mock observations. In that work, it was concluded that the code effectively reconstructs the qualitative evolution of the galaxies with the fossil record method. At younger ages (from the observed time), the code quantitatively recovers the stellar properties. During this process, ryPipe3D can be summarized as follows:

- It extracts an integrated central spectrum to estimate the initial value of the redshift and kinematics.
- It performs a spatial binning across the FoV of the input datacube to target a signal-to-noise ratio (SNR) of 50 per bin. The SNR is defined within a spectral window that the user can modify.
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2 https://archive.eso.org/wdb/wdb/eso/eso_archive_main/query?prog_id=099.B-0193

3 The reported seeing on the weather logs at Paranal during the observation night was $0\cdot47$, see https://www.eso.org/obs/ui/

4 https://gitlab.com/pypipe3d/pypipe3d/

5 The SSP libraries are available at http://ifs.astrosu.unam.mx/pyPipe3D/templates/
3 ANALYSIS

3.1 Holm15A Surface Brightness Modeling

Our principal objective is to analyze, model, and characterize the astronomical objects hidden by the brightness of Holm15A. To perform this task, we first correct the MUSE datacube by the galactic extinction with the use of the Schlafly & Finkbeiner (2011) galactic dust extinction maps and with the Fitzpatrick (1999) extinction law. After this correction, we model the surface brightness (SB) distribution of Holm15A across the FoV of the MUSE WFM. For this purpose, we first run rvPipe3 over the full datacube to obtain the cube of the stellar model of Holm15A. Then, we integrate the cube of the stellar model of Holm15A. Then, we integrate the cube of the stellar model through their full spectral axis (4750 – 9300Å) to obtain a high SNR collapsed image. We fit the SB isophotes using ellipses with the zero-point, semi-major axis (a), semi-minor axis (b), and rotation angle (Φ) as free parameters. We use 15 flux logarithmic spaced isophotes covering all the FoV along the major axis of Holm15A. We show these isophotes in the left panel of Figure 1 with their corresponding fitted ellipses. Then, to generate a first model of the SB profile of Holm15A, we parameterize the eccentricity (defined as $e = \sqrt{1 - (b/a)^2}$) profile in terms of the semi-major axis a. The parameterization can be well represented by:

$$e(a) = \frac{2Ae}{\pi} \arctan \left( \frac{a\pi}{2\sigma_e} \right). \quad (1)$$

Figure 2 shows the best fit of the eccentricity profile with $A_e = 0.73$ and $\sigma_e = 4.45$ (4.77 kpc at z = 0.056). The value of $\sigma_e$ marks the brake point where the circularization of the isophotes ends, and a constant eccentricity value dominates the eccentricity profile. For the rotation angle Φ, we define a constant Φ profile to model the SB distribution. For that objective, we obtain the median value of Φ of all the fitted ellipses with a major-axis value larger than 2$\sigma_e$. The final value of Φ is $-34\degree.3 \pm 0\degree.9$.

We then use the isophotes levels to fit the SB profile with a Nuker profile (Lauer et al. 1995) defined as:

$$I(r) = 2^{(\beta-\gamma)/\alpha} I_0 (R_b/r)^{\gamma} \left[1 + (r/R_b)^{\alpha}\right]^{(\gamma-\beta)/\alpha}. \quad (2)$$

Defining the cusp radius as $R_{c} = R_{b} \left(\frac{1/2-\gamma}{\beta-\gamma}\right)^{1/\alpha}$ (López-Cruz et al. 2014), with $R_{b}$ as the brake radius. The cusp radius defines the scale where $d\log I/d\log r = -1/2$ and indicates the region where the SB profile becomes shallow (Mehrgan et al. 2019). In addition, Mehrgan et al. (2019) found that Holm15A has a non defined brake radius. Therefore, we will use the cusp radius $R_{c}$ as the core scale of Holm15A. In a forthcoming paper (Lopez-Cruz et al., in prep), we will explore in detail the profile of Holm15A.

To minimize the fitting space parameter of the SB fit, we use the fitted exponential values of the Nuker profile reported by López-Cruz et al. (2014), leaving $I_0$ and $R_b$ as free parameters. The values reported by López-Cruz et al. (2014) are $\alpha = 1.24$, $\beta = 3.33$ and $\gamma = 0.0$. We find that the best fit values to model the SB profile of Holm15A with a Nuker profile are $I_0 = 4.69 \times 10^{-18} \text{ergs/cm}^2/\text{arcsec}^2$ with a $R_c$ value of $4\°.31$ (4.63 kpc). For comparison, López-Cruz et al. (2014) found a $R_c = 4\°.26$ while Mehrgan et al. (2019) found a $R_c = 4\°.1$. Hence, our measurement of $R_c$ is consistent with both estimations. Figure 2 presents the best fit for the SB profile.

Therefore, we can reconstruct a two-dimension SB model with the fitted values of $A_e$, $\sigma_e$, $I_0$ and $\Phi$. After this step, we obtain a high-SNR collapsed flux map (integrating over the spectral axis) from the original MUSE datacube. By subtracting the SB model map from the flux collapsed map, we obtain a high-SNR two-dimensional residual map (see the right panel of Figure 1).

Then, we generate a three-dimensional SB cube model by fitting the SB distribution through all the spectral sampling of the original MUSE cube. To fit the SB models, we fix the value of $\Phi$ and fit the eccentricity and SB profiles (as described above) for each of the 3,682 spectral values of the MUSE spectral axis. Hence, we obtain an SB model cube with the exact spectral sampling of the original MUSE observation. Finally, we obtain a residual cube by subtracting the SB model cube from the original flux cube. The final residual cube contains all the spectral information of the astronomical objects without the stellar spectra of Holm15A.
For this fit, we follow the same procedure described in Section 3.1 by using a Sersic (1963) profile. We list these measurements in Table 1.

3.2 Spectral Analysis.

By visually inspecting the spectra of each object, we are able to classify them into three types: galaxies, quasars, and stars (see Table 1). We determine that objects F and I are a quasar and a field star, respectively. We measure the redshift of the quasar in object F by identifying the MgII(2800, CIII]1909 and SiIII]1892 emission lines. Those lines are typically strong emission lines in quasars (Vanden Berk et al. 2001). Due to the nature of the objects, we discard the star spectrum of the object I, and we separate analysis of the quasar spectrum of the object F in Appendix B. We cannot detect a stellar spectrum for objects K and O but we can identify an intense emission for the nebular lines of [OIII]4372, Hβ, and [OIII]4363, due to the absence of a well-defined stellar spectrum, we cannot apply the full spectral analysis (see below), and therefore we can only use the nebular emission lines to measure their redshifts.

For the remaining objects, we proceed to fully analyze their spectra by using the pvPIPE3D code. For illustrative purposes, we plotted all the central spectra for our objects in Figure 3 and 4. We extract the central spectra within 0.5 Re, and over-plotted the fitted stellar spectra model from pvPIPE3D. With the SPS of pvFIT3D, we can apply a fossil record reconstruction to study the galaxy evolution across the cosmic time. We follow the methodologies described in Ibarra-Medel et al. (2016); Lopez-Cruz et al. (2019); Ibarra-Medel et al. (2022) and in Lacerna et al. (2020) to reconstruct their specific star formation histories (ssFH). We briefly describe these methodologies below.

With the SSP decomposition obtained by pvPIPE3D, we use the SSP weights (fssp) to estimate the instantaneous star formation rate (SFR) at a given SSP age. The history of the instantaneous SFR at a given age is the star formation history (SFH), and it is defined as follows:

$$SFH(t_i) = \sum_j f_{ssp}(Z_j, t_i) \times L_n \times 10^{0.4A_V}$$

$$\times \frac{Y_*(Z_j, t_i)}{m_{ttt}(Z_j, t_i) A_{t_i}}$$

where fssp(Z_j, t_i) is the SSP weight for the metallicity Z_j and age t_i. The value of L_n represents the normalized flux used during the SSP analysis. In this case, we define the normalized flux as the integrated flux within 4500 – 5500Å in the rest-frame of each galaxy (see Lacerna et al. 2022). For the object M, we require to redefine this window as 3850 – 4250Å due to its high redshift. A_{t_i} is the extinction value obtained by the SSP fit, Y_*(Z_j, t_i) is the mass-to-
Figure 3. Central spectra at the observed wavelength within 0.5$R_e$ for objects A, B, C, D, E and G. For object F we plot the total spectrum within their region. The blue line in each spectrum represent the fitted Pseudo-Gaussian model. The vertical red lines represent the most prominent emission nebular lines, the vertical yellow lines represent the most prominent stellar absorption lines. The gray bands represent the D4000 index region, and the Fraunhofer G and b bands.

The ratio of the SSP with metallicity $Z_j$ and age $t_i$, $m_{\text{loss}}(Z_j,t_i)$ is the mass-loss factor of the SSP with age $t_i$ and metallicity $Z_j$. Therefore, the instantaneous mass growth that happens at age $t_i$ is $f_{\text{SSP}}(Z_j,t_i) \times \Delta_{\text{t}} \times 10^{0.4A_V} \times Y_\odot(Z_j,t_i)/m_{\text{loss}}(Z_j,t_i)$. $\Delta_{\text{t}}$ is the characteristic time gap between the SSP age $t_i-1$ and $t_i+1$. The ratio of these two quantities defines the SFR at age $t_i$. Finally, we can define the observed time SFR rate derived from the stellar population synthesis ($\text{SFR}_{\text{SSP}}$) as the average value of $\text{SFH}(t)$ within the last 20 Myr.
Similarly, we are able to reconstruct the accumulative stellar mass (ASM) distribution across the time as:

\[
M_*(> t) = \sum_{t_i}^{t} \sum_{j} f_{SSP}(Z_j, t_i) \times L_n \times 10^{0.4 A_V} \times Y_*(Z_j, t_i).
\]  

The main difference between the ASM and the accumulative SFH(t) is the correction of the mass-loss factor of each SSP. The ASM did not correct the mass-loss and always had a monotonic and positive increment. In addition, we calculate the formation ages at which the ASM reaches its 90% (\(T_{90}\)) and 50% (\(T_{50}\)) of the observed time total stellar mass. Finally, we define the specific SFH (sSFH) as:

\[
sSFH(t) = \frac{SFH(t)}{M_*(> t)}
\]
4 SPECTRAL RESULTS

We separate all our objects into three groups due to their redshifts: The first group is formed by objects A and B, and their redshifts (z = 0.0498, 0.0563) identify them as a possible galaxy cluster members of Abell 85. At z = 0.053, the age of the Universe is 12.9 Gyr. Hence, we use the SSP grid with 39 ages, with a maximum SSP age of 13.5 Gyr. The second group are objects C, D, E, G, H, J, K, L, and O. Those objects have redshift values around 0.58, and are candidates to be a galaxy group behind Abell 85. At z = 0.58, the Universe’s age is 8.1 Gyr; therefore, we use the SSP grid with 36 ages with a maximum SSP age of 8.5 Gyr. The third group contains only the object M with a z = 1.0126. The age of the Universe at z = 1.0126 is 5.9 Gyr. Hence, we use the SSP grid with 34 ages with a maximum SSP age of 6.25 Gyr. At the redshift of z = 1.0126, the Balmer jump is still visible within the spectral range of the MUSE instrument, and therefore it is possible to apply the fossil record method to the observed spectrum of object M. We listed in Table 2 all the final SSP properties for these objects.

4.1 Object A and B

The SB of object A shows evidence of a bar structure oriented along its major-axis. The spectral analysis shows that it is blue-shifted by 1,666 km/s from Holm15A. Taking into account that the reported velocity dispersion of Abell 85 is ≈ 750 km/s (Bravo-Alfaro et al. 2009; López-Cruz et al. 2014), the line-of-sight relative velocity of object A indicates that it could be kinematically decoupled from Abell 85. The relative velocity with the central galaxy of Abell 85 is larger than two times the escape velocity of the cluster (Serra et al. 2011).

Figure 5 (left panel) shows the SPS reconstruction of the ASM and the sSFH of object A at three radial bins: R < 0.5R_e, 0.5R_e < R < R_e, and R_e < R < 1.5R_e. The sSFH shows evidence of a constant star formation rate at all radii with two dominant bursts, one at the age of ≈ 10 Gyr and a second at the age of ≈ 2.3 Gyr. After that, the galaxy suffers a rapid star formation (SF) shutdown that begins at the central part of the galaxy. In the central region, another SF episode begins at ≈ 130 Myr. This SF episode reactivates the SFR at the central region and has a peak (log sSFR ≈ −11.7 dex) at ≈ 40 Myr. After this peak, the SF slowly decreases at its present value (log sSFR = −11.1 dex). The ASM shows that the second burst at ≈ 2.3 Gyr contributes to the assembly of at least half of the total mass of object A. The assembly mode is almost uniform at all radii until the age of ≈ 2.5 Gyr, where the inside-out assembly mode dominates. The T_{50} age of object A is 4.1 Gyr, with a T_{90} of 2.1 Gyr.

Object B did not show any evidence of a bar structure like the object A. Its redshift shows that object B has a relative velocity with Holme15A of 280 km/s, implying that it is kinematically linked to the Abell 85 system. The fossil record reconstruction shows a similar but not equal sSFH as object A. For object B, we observe a first SF burst at late epochs (≈ 10 Gyr) from which its sSFR declines, and it reaches a minimum at the age of ≈ 600 Myr. After this minimum, object B shows a new star forming burst that reaches its peak at ≈ 40 Myr (see right panels of Figure 5). The ASM shows a constant rate on the mass assembly until 2 Gyr, and it is dominated by an inside-out assembly mode (Ibarra-Medel et al. 2016). It has a T_{50} of 8.7 Gyr and a T_{90} of 4.0 Gyr.

Both objects have light-weighted ages older than 1.5 Gyr, with light-weighted metallicities below the solar value (see cols 4, 5, 6 and 7 of Table 2). The difference between the mass and light-weighted ages are 0.43 and 0.4 dex for objects A and B. The difference between the mass and light-weighted metallicities are 0.06 and 0.07 dex each. The difference between the light and mass-weighted values traces the differences among the old and young stellar populations (Panter et al. 2008; Plauchu-Frayn et al. 2012; Lacerna et al. 2020). In this case, the differences among the light and mass metallicities for both
objects give evidence of a possible rejuvenation due to the in-fall of pristine gas (Maiolino & Mannucci 2019; Camps-Fariña et al. 2022). The in-fall of this gas could dilute the gas metallicity and feeds the last starburst observed on the sSFHs of objects.

4.2 Objects C, D, E, G, H, J, K, L and O

These objects are candidate members of a galaxy group with an average redshift of 0.5814 ± 0.001. We hereafter call this group as J004150-091812, and we present a complete analysis for the group in Section 5. In Figure 6, we present the ASM and sSFH for each object of this group. From the sSFH, we can classify our objects into interacted objects, star-forming objects, and intermediate objects.

**Interacted objects:** This group consists of objects C, D, E and L. The SPS analysis of these objects return a set of sSFH’s with evidence of past interactions. They have common SF burst at similar epochs among each other. In this aspect, López-Cruz et al. (2019) present evidence of a sheared star formation history among members of the Seyfert’s Sextet galaxy group. The common SF bursts trace the epochs when the galaxies were crossing (Hickson et al. 1992; Plauchu-Frayn et al. 2012), and therefore, interacted with galaxy members of the same group. Our fossil record analysis gives evidences of a mutual interaction between objects C, D, E...
and L. These objects have a long SF burst that begins at the age of \( \approx 6 \) Gyr and start to decline at \( \approx 3 \) Gyr. They also have a weak SF burst that begins at \( \geq 300 \) Myr with a maximum at the age of \( \approx 150 \) Myr. This weak SF burst is not enough to re-activate their sSFR and is rapidly quenched. For the case of object D, the shared SF burst is only present at its outer region (\( R > 0.5 R_{50} \)), with an internal region, completely quenched after the age of \( \approx 1 \) Gyr. Their sSFR show an outside-in assembly mode, with an average \( T_{50} \) (\( T_{50} \)) age of 2.8 (5) Gyr (see cols 9 and 10 of Table 2). Their mass-weighted ages have an average value of 4.5 Gyr, while their light-weighted ages have an average of 3.5 Gyr. Their D4000 index have an average value of 1.9 dex. The mass and light-weighted stellar metallicities have an average value (0.08 dex), which is slightly supersolar (Table 2 cols 6 and 7).

**Star formation objects:** This group contains objects G, H and objects K and O. We cannot detect a stellar spectra for objects K and O, and therefore we cannot estimate the sSFR and the ASM; however, we put them within this group due to their strong nebular emission lines for \([\text{OII}], \lambda 3728, \text{H}\beta, [\text{OIII}], \lambda 4959, 5007\). The sSFR for objects G and H show the same initial SF burst at an age of \( \approx 6 \) Gyr. After this initial burst, their sSFR decreases until an age of \( \approx 1 \) Gyr, where the sSFR reaches a constant value (log \( sSFR \approx -10.0 \) dex). The sSFR remains constant until an age of \( \approx 200 \) Myr, where objects G and H start to differentiate. Object G suffers a more steep decrease on their sSFR reaching an observed time sSFR of \(-11.2 \) dex. On the other hand, object H maintains a slower decrement on their sSFR reaching a value of log \( sSFR \approx -10.7 \) dex at the moment of the observation. The ASM of objects G and H show an inside-out assembly mode only for their internal regions (\( R < 0.5 R_{50} \) vs \( 0.5 R_{50} < R < R_{50} \)).

Both objects have \( T_{50} \) ages younger than 5.2 Gyr, with younger \( T_{50} \) ages (\( < 1.5 \) Gyr). Their light (mass) weighted ages have an average value of 0.9 (3.6) Gyr and their average light (mass) weighted stellar metallicities are \(-0.55 (-0.25) \) dex (see Table 2). The difference among the mass and light weighted metallicities are 0.2 and 0.4 dex for object G and H. The positive value of this difference indicates a possible metallicity dilution by the in-fall of pristine gas like objects A and B but in a much intense rate. The spectra of objects G and H (see Figure 3 and Table 2) show the emission of the nebular lines for \([\text{OII}], \lambda 3728, \text{H}\delta, \text{H}\gamma, \text{H}\beta, \) and \([\text{OIII}], \lambda 4959, 5007\), with H displaying the most strong lines. These emission lines indicate the existence of an intense and recent SF burst. The stellar spectra show the existence of strong Balmer and Ca absorption lines. Their  

**Figure 7.** Left panel: The ASM distributions for object M at three radial regions: \( R < 0.5 R_{50} \) (blue), \( 0.5 R_{50} < R < R_{50} \) (green), and \( R_{50} < R < 1.5 R_{50} \) (red). Right panel: The sSFR for object M at the same radial bins and the same color code of the left panel. The shaded color areas are the 1\( \sigma \) variance for 100 iterations. The vertical gray lines represent the SF burst and quenching episodes described in the text.

**Table 2.** The SSP properties from the SPA and spectral analysis within one effective radii.

| ID | \( M_* \) \( [M_\odot] \) | D4000 | \( \text{Age}_{1w} \) [Gyr] | \( \text{Age}_{mew} \) [Gyr] | log \( Z_{1w} \) \( [Z/Z_\odot] \) | log \( Z_{mew} \) \( [Z/Z_\odot] \) | log sSFR \( R_{50}^p \) [Gyr] | \( T_{50} \) [Gyr] | \( T_{50} \) [Gyr] |
|----|------------------|----------|-----------------|-----------------|-----------------|-----------------|-----------------|----------------|----------------|
| A  | \( 5.8 \pm 0.1 \times 10^3 \) | 1.5 \pm 0.1 | 4.1 \pm 0.1 | -0.06 \pm 0.01 | -0.01 \pm 0.01 | -11.1 \pm 0.1 | 4.1 \pm 0.1 | 2.1 \pm 0.1 |
| B  | \( 3.7 \pm 0.1 \times 10^3 \) | 2.9 \pm 0.1 | 7.4 \pm 0.2 | -0.24 \pm 0.01 | -0.16 \pm 0.01 | -11.1 \pm 0.1 | 8.7 \pm 0.3 | 4.0 \pm 0.1 |
| C  | \( 1.3 \pm 0.1 \times 10^3 \) | 1.82 \pm 0.01 | 3.7 \pm 0.1 | 4.5 \pm 0.1 | +0.15 \pm 0.02 | +0.17 \pm 0.02 | -13.8 \pm 0.2 | 4.8 \pm 0.3 | 3.1 \pm 0.1 |
| D  | \( 4.3 \pm 0.7 \times 10^3 \) | 1.89 \pm 0.02 | 3.5 \pm 0.1 | 4.6 \pm 0.2 | +0.07 \pm 0.01 | +0.06 \pm 0.02 | -13.7 \pm 0.6 | 5.1 \pm 0.5 | 2.7 \pm 0.1 |
| E  | \( 1.1 \pm 0.1 \times 10^3 \) | 1.92 \pm 0.02 | 3.5 \pm 0.1 | 4.4 \pm 0.2 | +0.11 \pm 0.03 | +0.07 \pm 0.05 | 5.0 \pm 0.2 | 2.9 \pm 0.2 |
| G  | \( 3.9 \pm 0.4 \times 10^3 \) | 1.46 \pm 0.02 | 1.1 \pm 0.02 | 3.9 \pm 0.4 | -0.52 \pm 0.07 | -0.32 \pm 0.06 | -11.2 \pm 0.2 | 5.2 \pm 0.6 | 1.5 \pm 0.1 |
| H  | \( 1.1 \pm 0.3 \times 10^3 \) | 1.30 \pm 0.02 | 0.6 \pm 0.1 | 3.3 \pm 0.3 | -0.59 \pm 0.09 | -0.19 \pm 0.07 | -10.7 \pm 0.2 | 4.8 \pm 0.5 | 0.9 \pm 0.2 |
| J  | \( 5.0 \pm 0.3 \times 10^3 \) | 1.82 \pm 0.02 | 3.6 \pm 0.2 | 4.6 \pm 0.3 | -0.02 \pm 0.03 | 0.0 \pm 0.04 | -13.5 \pm 0.3 | 5.3 \pm 0.6 | 2.8 \pm 0.2 |
| L  | \( 2.6 \pm 0.2 \times 10^3 \) | 1.85 \pm 0.02 | 3.4 \pm 0.1 | 4.6 \pm 0.2 | -0.00 \pm 0.03 | +0.04 \pm 0.05 | -13.1 \pm 0.4 | 5.3 \pm 0.3 | 2.7 \pm 0.1 |
| M  | \( 9.0 \pm 1.5 \times 10^3 \) | 1.30 \pm 0.02 | 0.5 \pm 0.1 | 4.0 \pm 0.2 | -0.62 \pm 0.08 | -0.23 \pm 0.08 | -10.8 \pm 0.1 | 5.2 \pm 0.3 | 2.4 \pm 0.2 |

*\( \lambda \) The spectral coverage for objects A and B didn’t reach the Balmer jump.

*\( b \) Object E didn’t returns a present day sSFR \( R_{50}^p \) value.

*\( c \) \( Z_\odot = 0.019 \).
star formation burst at the age of \( \approx 5 \) Gyr, followed by a rapid SF quenching that drops the sSFR at a minimum value of \( \approx -11.5 \) dex at the age of \( \approx 830 \) Myr. After this age, the sSFR is reactivated and reaches an sSFR peak (\( \approx -10.2 \) dex) at \( \approx 280 \) Myr. Then, the sSFR slowly decreases until its present-day value (-10.8 dex). The light (mass) weighted age of object A is 0.5 (4) Gyr while its metallicity has sub-solar values of -0.62 (-0.23) dex. Its D4000 index has a value of 1.3 dex and agrees with the measured light-weighted age.

5 ANALYSIS OF J004150-091812

In this section, we explore the properties of the galaxy group J004150-091812 as a whole. We need to consider that J004150-091812 is behind of the massive halo of Holm15A, that contains one of the biggest SMBH (Mehrgan et al. 2019; López-Cruz et al. 2014), and therefore the projected sky positions of objects C, D, E, G, H, J, K, L and O can be perturbed by the strong/weak lensing of the gravitational potential of Holm15A. To explore this possibility, we analyze the image distortion using the LensStool code (Kneib et al. 1996; Jullo et al. 2007; Jullo & Kneib 2009). With this code, we can model and quantify the image distortion of the source and trace the amplification of the gravitational lens of Holm15A.

5.1 Lensing Modelling

The observed SB distribution of Holm15A and the spectroscopic analysis of objects A and B show that a simple profile can model the total mass distribution of Holm15A. We show in the previous section that object A is not part of the cluster and have a total stellar mass of \( 5.8 \times 10^9 \) M\(_\odot\), and object B has a total stellar mass of \( 3.7 \times 10^9 \) M\(_\odot\). These masses are one order of magnitude lower than the most recent mass estimation (\( 4 \times 10^{10} \) M\(_\odot\)) of the SMBH in the center of Holm15A (Mehrgan et al. 2019). Therefore, the mass contribution of objects A and B to the total potential model is negligible. Hence, we can model the total mass distribution using only one potential. For this aim, we use a dual pseudo isothermal elliptical mass distribution (PIEMD Limousin et al. 2005; Eladástööt et al. 2007) that is defined as:

\[
\rho(r) = \frac{\rho_0}{(1 + r^2/R_0^2)^{\nu}} \left(1 + r^2/R_0^2\right)^{\nu}
\]

We use the fitted values of our SB modeling of Holm15A to fix the ellipticity and position angle for the projected mass distribution.

In addition, we use the mass profile measured by Mehrgan et al. (2019) to constrain the values of \( \rho_0 \), R\(_\text{cut}\) and R\(_\text{core}\). Mehrgan et al. (2019) estimate the mass profile by detailing modeling the stellar kinematics of Holm15A. We also model the mass contribution from the Holm15A SMBH to the total projected mass distribution as a Dirac delta function with a peak that equals the total mass of the SMBH measured by Mehrgan et al. (2019). For the lensing modeling, we consider all the galaxy members of J004150-091812 as single images each. We do not find any evidence of the existence of any strong lensed image that could form an arc image or multiple images from the same source. The absence of any strong or weak lensed image, will return in an unconstrained lens model. Therefore, it is a good choice to obtain the lens model by constraining the mass profile with the Mehrgan et al. (2019) estimation. In Figure 8, we show the best lensed SB model obtained with LensStool. It shows the models for the SB distributions for the 9 group galaxy candidate members and over-plotted the flux residuals of the SB fit of Holm15A.

The mass model returned by LensStool is a PIEMD potential with R\(_\text{core}\) =14.54 kpc, R\(_\text{cut}\) =1077.3 kpc and \( \rho_0 = 9.5 \times 10^7 \) M\(_\odot\)kpc\(^{-3}\). With these values, we can estimate the total enclosed mass at a given radius (see Figure 9). Following the analysis presented

**Figure 8.** SB of the lensed images for each candidate member of J004150-091812. The black lines represent the SB isocountours of the images modeled by LensStool. The color map represents the residual map of Holm15A described in Figure 1. The color bar represents the observed SB flux.

**Figure 9.** The cumulative mass profile of Holm15A is estimated with LensStool. The red line represents the three-dimensional enclosed mass profile. The blue line represents the two-dimensional projected cumulative mass profile. The purple dashed line profile represents the cumulative mass profile predicted by Mehrgan et al. (2019). The vertical gray lines represent the Mehrgan et al. (2019) SOI scale, the R\(_e\) scale from the eccentricity profile of Holm15A, and the R\(_g\) scale from the Nkker profile fit of Holm15A.
by López-Cruz et al. (2014), we can use the cusps radii of our Nuker profile to estimate the size of the sphere of influence (SOI) of the SMBH. Therefore, the total mass contained within $R_S$ equals to $7.7 \times 10^{10} M_\odot$. On the other hand, the drop in the measured eccentricity of the isophotes in the inner radii of Holm15A (Figure 2) can be related to the dynamical mixing of the SMBH (López-Cruz et al. 2014). Therefore, the value of $\sigma_g$ could be used as a tracer of the SOI: its total mass contained within this scale is $8.1 \times 10^{10} M_\odot$. Finally, using the value of SOI ($R_{\text{SOI}} = 3.8$ kpc) measured by Mehrghan et al. (2019), we found a total enclosed mass of $6.1 \times 10^{10} M_\odot$. The PIEMD obtained from Lenstool agrees with the total cumulative mass profile measured by Mehrghan et al. (2019). In this way, we can use the lens model derived by Lenstool to correct the sky projected positions for the galaxy members of J004150-091812.

5.2 Scale of J004150-091812

In Figure 10, we show the positions of all group members of J004150-091812 with and without the perturbations of the gravitational lens of Holm15A. With the positions of the group members, we calculate the group centroid by weighting its positions by the logarithm of their stellar masses:

$$\delta_g = \frac{\sum_i \log_{10} M_{*i} \delta_i}{\sum_i \log_{10} M_{*i}}, \quad (9)$$

$$\sigma_g = \frac{\sum_i \log_{10} M_{*i} \sigma_i}{\sum_i \log_{10} M_{*i}}, \quad (10)$$

For weighting the object K and O, we use the lowest measured stellar mass of the group members as an upper limit of their stellar masses. We calculate the group centroid with and without the correction of the gravitational lens. Both centroids are almost identical, with a small difference of $\approx 0.1''$ in declination. The final centroid of the galaxy group is $\alpha = 00h41m50.4s, \delta = -09d18m11.86s$.

With the centroid, we calculate the scale of the group ($R_g$). The FoV of the MUSE-WFM observation can bias this scale, and therefore we consider this scale as the lower limit of the real scale of the galaxy group. We calculate the scale of the group as the average distance from the centroid weighted by the stellar mass of each member:

$$R_g \geq \frac{\sum_i \sqrt{(\delta_i - \delta_g)^2 + (\alpha_i - \alpha_g)^2} \log_{10} M_{*i}}{\sum_i \log_{10} M_{*i}}, \quad (11)$$

Considering the correction from the Holm15A lens, we obtain a value of $R_g = 22''.3 \pm 0''.4$ or $146 \pm 3$ kpc. Without this correction, we obtain a value of $R_g = 24'''.8 \pm 0''.4$ or $163 \pm 3$ kpc (see Figure 10).

5.3 Dynamical Mass of J004150-091812

From the measured redshift values of the galaxy members of J004150-091812, we measure its line-of-sight (LOS) velocity dispersion ($\sigma_{g, \text{LOS}}$). We estimate the 68.2 and 34.1 percentiles and determine the $1 - \sigma$ LOS velocity value of the galaxy members. The final velocity dispersion value is $\sigma_g = 622 \pm 300$ km/s. With the scale and the velocity dispersion, we use the standard definition of the virial theorem (Zwicky 1937; Girardi et al. 1998) to estimate the dynamical mass of the group:

$$M_{\text{dyn}} \approx A \frac{R_g \sigma_{g, \text{LOS}}^2}{G}, \quad (12)$$

where $A$ is a scaling factor that takes into account the geometry of the system and the dynamical state in order to estimate an unbiased value of the dynamical mass of the system (Robotham et al. 2011; Aquino-Ortiz et al. 2020). The value of $A$ will be greater or equal to one, with $A = 1$ as the ideal case. This study will express the dynamical mass in terms of $A$ for simplicity. $G$ is the gravitational constant in the corresponding units. Finally, we obtain that J004150-091812 has a lower limit of the dynamical mass of $M_{\text{dyn}} \geq 1.2 \pm 0.8 \times 10^{13} M_\odot A$, with the correction of the Holm15A lens. Without using the lens correction, we obtain a value of $M_{\text{dyn}} \geq 1.5 \pm 0.8 \times 10^{13} M_\odot A$. It is important to note that this mass estimation assumes that the J004150-091812 galaxy group is completely relaxed, however this assumption is not necessary true. We observe evidence that J004150-091812 is actually in an assembly process with at least three merger trees (see discussion below).

6 SUMMARY AND DISCUSSION

The principal aim of this study is the identification and characterization of the principal astronomical objects hidden behind the Holm15A SB. This characterization is a crucial step in separating structures that are physically linked within Holm15A from those that are external objects. This step will clean the path for a more
depth study on the nature of the SMBH within Holm15A. For this aim, we use archive MUSE IFU observations of Holm15A and model and subtract its spectral contribution. Looking at the residuals, we detect 14 major structures from which we could extract their spectral information once cleaned from the Holm15A emission. We analyze the spectral information of all the objects and determine that ten objects present a well-defined galaxy spectra from which we can apply the fossil method to explore their past evolution and interlinkage among each other. From the spectral analysis, we find the following results:

- The spectroscopic analysis confirms that all the 14 detected objects are not part of Holm15A.
- Two objects (object F and I) are point sources that came from a quasar emission at z=1.5637 (object F) and a field star (object I).
- We detect two near objects on the vicinity of Holm15A (object A and B). Object A can be classified as a late-type galaxy with a well-defined bar structure. It has a redshift value of 0.0498, from which we can conclude that it is not dynamically linked to the Abell 85 galaxy cluster. Object B can be classified as an early-type galaxy with a redshift value of 0.0563, that confirms that it is a galaxy member of the Abell 85 cluster. The SSP properties of both objects indicate the existence of two principal SSP components, one young (3 < Gyr) with subsolar metallicity and one old (4 > Gyr) with also subsolar metallicity but heavier than the young population. Therefore, the SSPs properties support the scenario of a possible rejuvenation of the SF activity with the dilutions of the gas content due to the in-fall of pristine gas (Maiolino & Mannucci 2019; Camps-Fariña et al. 2022). This mechanism explains the halt in the SF quenching observed on both objects.

- Object M is the farthest object that we detect with a well-defined galaxy spectrum. It has a redshift value of 1.0126; at that redshift, the universe had an age of 5.9 Gyrs. Therefore, the SPS analysis of object M allows us to access the archaeological information at the cosmic noon without suffering from a significant bias inherited from the archaeological inferences limitations (Ibarra-Medel et al. 2019). Their nebular emission lines confirm the archaeological view of a recent reactivation of the SFR. In addition, their SSP properties indicate a very strong dilution of the SSP metallicities between young and old populations with a difference of 0.39 dex. Its stellar spectra present a very well-defined stellar absorption line spectrum that indicates a very strong dilution of the SPS metallicities between the old and young stellar populations, indicating the existence of a mechanism that provides fresh gas that can feed and sustain the observed SFR. The objects G and H did not have a well-defined stellar galaxy spectrum, and therefore we cannot apply our spectral analysis. On the other hand, we can detect an strong nebular emission that indicates a intense and recent star formation activity in a very similarly way as objects G and H. In the same direction as object J, the difference among the sSFR with the other members of the group didn’t imply that objects G, H, K and O aren’t members of J004150-091812. Objects G, H and O (and possibly K and O) share a very similar sSFR with common sSFR episodes. Therefore, these galaxies could form a sub-group that recently falls into the gravitational potential of J004150-091812, showing another merger tree on the assembly history of J004150-091812. The stellar spectra of objects G and H show very intense and well-defined stellar absorption lines. However, these galaxies cannot be identified as E+A due to the intense emission of [OII]λ3728. On the other hand, these galaxies can be the precursors of E+A galaxies, with a future SF quench after they completely join into the J004150-091812 galaxy group and suffers multiple galaxy mergers (Bekki et al. 2005).

- We estimate the mass and size of J004150-091812 using the measured sky positions and redshifts for each galaxy member. To estimate the scale and the central position of J004150-091812, we first correct the sky positions of each member from the optical perturbations done by the gravitational lensing of the Holm15A potential. To perform such correction, we use the Lensestoch software. With the lens correction, we estimate the scale of J004150-091812 as the stellar mass-weighted distance of each member to the centroid. Considering the lens correction, we find the scale of 146±3 kpc. Without this correction, we find a scale of 163±3 kpc. It is important to note that the FoV of the MUSE WFM biases these scales, and therefore, we only consider those scales as lower limits of the real scale of J004150-091812. We find that J004150-091812 has a velocity dispersion of 622±300 km/s. Assuming that J004150-091812 is dynamical relaxed, its dynamical mass has a value of $M_{\text{dyn}} \approx 1.2 \pm 0.8 \times 10^{13} M_\odot$ when we consider the lens correction and $M_{\text{dyn}} \approx 1.5 \pm 0.8 \times 10^{13} M_\odot$ when we discard the lens correction. However, the SFHs of the galaxy members of J004150-091812 indicate that the galaxy group is in an assembly process and therefore it is not in a virial equilibrium. Following the mass-radius scale relationships explored by Chiosi et al. (2020), it is expected that a galaxy group with a measured mass of $\approx 10^{13} M_\odot$ would have a scale of $\approx 316$ kpc. For J004150-091812, we measure a scale of half than it is expected. The bias of the un-virialized stage of J004150-091812 overestimates its dynamical mass, explaining the differences in the galaxy group scales. In addition, due to the limitations of the FoV on the scale estimation of J004150-091812, we are not available to classify J004150-091812 as a compact group according to the Hickson (1982) classical definition.

- As a secondary result from this analysis, we propose using the circularization scale $\tau_r$ of the ellipticity profile of Holm15A as an indirect estimation of the SMBH SOI scale. We will explore this possibility in a forthcoming paper.
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8 DATA AVAILABILITY

The data underlying this article are available at the ESO public archive for the MUSE program ID 009.B-0193 with the following URL link: https://archive.eso.org/wdb/wdb/eso/eso_archive_main/query?prog_id=009.B-0193. We also put public available all the extracted datacubes for all our 14 objects at the next URL link: https://github.com/hjibarram/Holm15A_objects_datacubes.

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MaNGA team for creating this tool, and the CONACyT-180125 project for supporting them.
Figure A1. Measured FWHM PSF within the MUSE observation of Holm15A. The red dashed line represents the best fitted value of the PSF as a function of the wavelength using the SB profile of object I. The blue line represents the best fitted value of the PSF for object F. The black dashed line is the smoothed mean value of the two objects.

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APPENDIX A: PSF MODELING

This appendix describes the measurement of the point spread function (PSF) and, therefore, the effective spatial resolution of the Holm15A MUSE WFM observation. For this aim, we use the extracted regions of objects F and I (see Figure 1). We select each region to contain only the objects F and I without any other structure within it. The object F is a quasar at z=1.5637, and object I is a field star, and therefore are the ideal objects to measure the PSF within the MUSE datacube. We extract the flux maps for each spectral sampling of the datacube and fit a two-dimensional PSF SB profile. We assume that the PSF has an SB profile that follows a Moffat (Moffat 1969; Trujillo et al. 2001) shape with the following form:

\[ F(i, j) = A_x \times \left(1 + \frac{(i-x_0)^2 + (j-y_0)^2}{\alpha^2}\right)^{-\beta}, \]  

(A1)

where \( A_x \) is the peak value of the PSF profile, \( x_0 \) and \( y_0 \) are their centroids, and \( \alpha \) is the dispersion of the profile and \( \beta \) traces the size of the "wings" of the PSF. As \( \beta \) increases, the PSF "wings" decreases and the profile asymptotically tends to a Gaussian shape (Trujillo et al. 2001). During the fitting, we left as free parameters the values of \( A_x \), \( x_0 \), \( y_0 \), \( \alpha \) and \( \beta \). We obtain the best fit values for the SB profile for objects F and I at each spectral value of the data cube. Finally, we estimate the PSF FWHM as \( 2\alpha \times \sqrt{2\Gamma/\beta} - 1 \). In Figure A1, we plot the final measured values of the PSF within the MUSE data cube in terms of the wavelength.

We find that the value of \( \beta \) remains constant thought the wavelength axis with a value of \( \beta = 2.5 \pm 0.2 \) dex. The MUSE PSF

contains a more extended wing size in comparison of a Gaussian PSF.

APPENDIX B: SPECTRAL MODEL OF OBJECT F

With the PSF model, we can reconstruct the SB model cube for object F, to extract the PSF flux spectrum. The PSF flux spectrum is the integral of the PSF SB model at each spectral point and is defined as: \( F_i = A_i \frac{\pi \alpha^2}{\beta} \). With the extracted PSF spectrum, we proceed to model the quasar spectrum of object F. To model the quasar spectrum, we use the PyQSOFr tool\(^8\) (Guo et al. 2018, 2019; Shen et al. 2019). This tool fits the galaxy host continuum, the power-law contribution, the FeII lines, and fits the broad and narrow components from the quasar emission lines (Vanden Berk et al. 2001).

In Figure B1, we show the PSF quasar spectrum for object F, with the fitted models delivered by PyQSOFr. We measure a quasar power-law with a slope of -1.54 dex, with an FWHM for the MgII[2800] emission line broad component of 2,800 km/s. We also measure the continuum flux at \( \lambda L_{3000} = 21 \times 10^{44} \) erg/s. Therefore, using the MgII estimator for the black hole (BH) mass (Wang et al. 2009), we measure a BH mass of \( 1.3 \times 10^9 M_\odot \). With the PSF quasar spectrum model, we obtain the map of residuals from the extracted region of object F. From the residual map, we cannot find any structure associated with the host galaxy of object F. Hence the spectrum observed for object F is completely dominated by the quasar emission.

This paper has been typeset from a TeX/LATeX file prepared by the author.

\(^8\) https://github.com/legolason/PyQSOFit