The SAMI Galaxy Survey: Stellar Population Gradients of Central Galaxies

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Abstract

We examine the stellar population radial gradients (age, metallicity, and \([\alpha/Fe]\)) of 96 passive central galaxies up to \(\sim 2 R_e\) in the SAMI Galaxy Survey. The targeted groups have a halo mass range of \(11 < \log(M_{200}/M_\odot) < 15\). The main goal of this work is to determine whether central galaxies have different stellar population properties when compared to similarly massive satellite galaxies. For the whole sample, we find negative metallicity radial gradients, which show evidence of becoming shallower with increasing stellar mass. The age and \([\alpha/Fe]\) gradients are slightly positive and consistent with zero, respectively. The \([\alpha/Fe]\) gradients become more negative with increasing mass, while the age gradients do not show any significant trend with mass. We do not observe a significant difference between the stellar population gradients of central and satellite galaxies at fixed stellar mass. The mean metallicity gradients are \(\Delta[Z/H]/\Delta \log (r/R_e) = -0.25 \pm 0.03\) for central galaxies and \(\Delta[Z/H]/\Delta \log (r/R_e) = -0.30 \pm 0.01\) for satellites. The mean age and \([\alpha/Fe]\) gradients are consistent between central and satellite galaxies, within the uncertainties, with a mean value of \(\Delta \log (\text{Age}/\text{Gyr})/\Delta \log (r/R_e) = 0.13 \pm 0.03\) for centrals and \(\Delta \log (\text{Age}/\text{Gyr})/\Delta \log (r/R_e) = 0.17 \pm 0.01\) for satellites and \(\Delta[\alpha/Fe]/\Delta \log (r/R_e) = 0.01 \pm 0.03\) for centrals and \(\Delta[\alpha/Fe]/\Delta \log (r/R_e) = 0.08 \pm 0.01\) for satellites. The stellar population gradients of central and satellite galaxies show no difference as a function of halo mass. This evidence suggests that the inner regions of central passive galaxies form in a similar fashion to those of satellite passive galaxies, in agreement with a two-phase formation scenario.

Unified Astronomy Thesaurus concepts: Galaxy abundances (574); Galaxy environments (2029); Galaxy evolution (594)

1. Introduction

In the hierarchical galaxy formation paradigm, galaxy assembly and the growth of dark matter halos are closely linked. The central galaxies in dark matter halos are generally the brightest galaxies in those systems (also known as brightest cluster galaxies (BCGs) and brightest group galaxies (BGGs), hereafter referred to as central galaxies). Due to their privileged position at the bottom of the gravitational potential, they are predicted to have undergone a higher rate of mergers and, therefore, to generally be more massive than other galaxies in those systems (e.g., de Lucia & Blaizot 2007). Despite being very luminous and relatively easy to detect, the formation history of central galaxies is complex and not yet fully understood (e.g., Lidman et al. 2013; Lin et al. 2013; Oliva-Altamirano et al. 2014; Davies et al. 2019).

Luckily, the stellar populations of galaxies give insight into their formation histories. The fraction of stars with a given age is a record of the star formation history of the galaxy, while the metallicity gradient is strongly correlated with the galaxy’s assembly history, and the abundance of alpha elements relative to iron elements \((\alpha/Fe)\) gives information on the star formation timescale in the different regions of the galaxy.

In particular, studying how the stellar populations vary with radius can shed light on whether the evolutionary histories of central galaxies are different from those of satellite galaxies, which are not in a privileged position in the gravitational well.

Massive galaxies at \(z \approx 2\) are already found to be quiescent but compact, with an effective radius \((R_e)\) half the size of galaxies of similar mass in the local universe (e.g., Daddi et al. 2005; Trujillo et al. 2006; van Dokkum et al. 2008). Hydrodynamical-zoom cosmological simulations found that massive galaxies likely form in a two-phase formation scenario (e.g., Naab et al. 2009). During the first phase, at high redshift, they grow by a rapid episode of in situ star formation, resulting in compact massive systems. The initial stellar metallicity gradient is set by the initial episode of star formation, with the metallicity decreasing outward in the galaxy (Larson 1974; Thomas et al. 2005). From this process, we would expect steep, negative metallicity gradients and flat age radial profiles. After \(z \approx 2\), these massive compact galaxies \((\log(M_*/M_\odot) > 10.5)\) are predicted to be quiescent and grow mostly by accreting...
mass through galaxy interactions that add stars to their outskirts (Hopkins et al. 2009; Naab et al. 2009; Oser et al. 2010).

In the simulations of Hirschmann et al. (2015) and Cook et al. (2016), galaxies that have experienced a greater number of interactions show flat or slightly positive age gradients due to old stars being added in the outer regions and shallower metallicity gradients produced by the mixing of the different metallicities of the accreted stars. In these simulations, the contributions from accretion start to be visible beyond 2 $R_e$ (seen observationally by Coccato et al. 2010; Montes et al. 2014). By observing the radial stellar population gradients of galaxies, we can infer their assembly history.

Several observational studies have explored the stellar population radial profiles of central galaxies using long-slit spectroscopy; Brough et al. (2007) and Loubser & Sánchez-Blázquez (2012) found that the age and [$\alpha$/Fe] gradients are mostly shallow and similar to those of other early-type galaxies (ETGs) in high-density environments. They also found a wide range of metallicity gradients, suggesting that these galaxies had very different assembly histories.

Recently, substantial progress on our understanding of the stellar populations of ETGs has been made thanks to the use of large integral field spectroscopy (IFS) surveys such as the Spectroscopic Areal Unit for Research on Optical Nebulae (SAURON; de Zeeuw et al. 2002), ATLAS3D (Cappellari et al. 2011), the Calar Alto Legacy Integral Field Array survey (CALIFA; Sánchez et al. 2012), MASSIVE (Ma et al. 2014), Mapping Nearby Galaxies at Apache Point Observatory (MaNGA; Bundy et al. 2015), and the Sydney-Australian-Astronomical-Observatory Multi-object Integral-Field Spectrograph Galaxy Survey (SAMIGS; Croom et al. 2012; Bryant et al. 2015). Using IFS enables the mapping of stellar populations across individual galaxies, rather than obtaining gradients from only one axis of the galaxy, as long-slit observations do.

Despite the increasing number of surveys, the studies of the stellar population gradients of ETGs are still not in agreement. For example, Kuntschner et al. (2010), studying 48 ETGs in the SAURON survey, found evidence for gradually shallower metallicity gradients ($\Delta[Z/H]/\Delta \log (r/R_e) > -0.3$, measured within 1 $R_e$) with increasing stellar mass for galaxies with masses greater than $10^{10.3} M_\odot$ and flat age gradients for the general population of ETGs. Similar results for metallicity gradients (within 1 $R_e$) were found by Li et al. (2018) in MaNGA galaxies with masses ranging from $10^9$ to $10^{12.3} M_\odot$. However, Goddard et al. (2017), studying MaNGA ETGs with stellar masses ranging from $10^9$ to $10^{11.5} M_\odot$, concluded that luminosity-weighted metallicity gradients (within 1.5 $R_e$) become slightly more negative with increasing stellar mass (with the relation having a slope of $-0.04 \pm 0.05$). Zheng et al. (2017) found weak or no correlation between metallicity gradients and stellar mass with the same survey ($\approx$570 MaNGA ETGs with stellar masses ranging from $10^{9.5}$ to $10^{11.5} M_\odot$; consistent with Goddard et al. 2017). The differences, however, can be explained in most cases by differences in sample selection (how the ETGs were selected and the galaxy stellar mass range studied). In the particular cases of Goddard et al. (2017) and Li et al. (2018), the differences are also likely to be due to the different definition of gradient used—linear radial fits ($\Delta[Z/H]/\Delta \log (r/R_e)$; Goddard et al. 2017) compared to logarithmic radial fits ($\Delta[Z/H]/\Delta \log (r/R_e)$; Li et al. 2018).

The MASSIVE survey found that massive ETGs ($M_*>4 \times 10^{11} M_\odot$) have shallow metallicity gradients ($\Delta[Z/H]/\Delta \log (r/R_e) = -0.3 \pm 0.1$) and no significant age or [$\alpha$/Fe] abundance ratios for this analysis. Section 3 outlines the procedure followed to define a consistent and reliable set of data. Section 4 presents our results that are then discussed in Section 5. Our conclusions are given in Section 6. SAMI adopts a $\Lambda$CDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2. Observations

The SAMI Galaxy Survey is a large, optical IFS (Bryant et al. 2015) survey of low-redshift ($0.04 < z < 0.095$) galaxies covering a broad range in stellar mass, $7 < \log_{10}(M_*/M_\odot) < 12$, morphology, and environment. The sample, with $\approx$3000 galaxies, is selected from the Galaxy and Mass Assembly Survey (GAMA; Driver et al. 2011) regions (group galaxies), as well as eight additional clusters, to probe higher-density environments (Owers et al. 2017).
The SAMI instrument (Croom et al. 2012), on the 3.9 m Anglo-Australian telescope, consists of 13 “hexabundles” (Bland-Hawthorn et al. 2011; Bryant et al. 2014) across a 1° field of view. In the typical configuration, 12 hexabundles are used to observe 12 science targets, with the 13th one allocated to a secondary standard star used for calibration. Moreover, SAMI also has 26 individual sky fibers to enable accurate sky subtraction for all observations without the need to observe separate blank sky frames.

2.1. Integral Field Spectra

The SAMI data consist of three-dimensional data cubes: two spatial dimensions and a spectral dimension.

The wavelength coverage is from 3750 to 5750 Å in the blue arm and 6300 to 7400 Å in the red arm, with a spectral resolution of $R = 1812$ (2.65 Å FWHM) and $R = 4263$ (1.61 Å FWHM), respectively (van de Sande et al. 2017), so that two data cubes are produced for each galaxy target. Only the blue arm is used to determine stellar population parameters, since there are only a few absorption features in the red wavelength range useful to this end.

The SAMI data reduction is fully described in Allen et al. (2015) and Sharp et al. (2015), and we give a brief summary here.

A dedicated SAMI Python package (that incorporates the 2DFDR package$^{12}$; Croom et al. 2004; Sharp & Birchall 2010) is used to perform bias subtraction and flat-field normalization, remove cosmic rays, and calibrate the absolute flux to reduce the raw SAMI observations (Allen et al. 2015). Each galaxy field was observed in a set of approximately seven 30 minute exposures that are aligned together by fitting the galaxy position within each hexabundle with a two-dimensional Gaussian and fitting a simple empirical model describing the telescope offset and atmospheric refraction to the centroids. The exposures are then combined to produce a spectral cube with regular 0.5 spaxels, with a median seeing of 2.2, such that $r > 0.181 d$. The median halo mass of $\mathcal{H}$-strong using the absorption and emission line properties of each SAMI spectrum. We select 843 passive galaxies; of these, 98 are central and 745 are satellite galaxies (Figure 1).

In this paper, we are particularly interested in whether the evolution of central and satellite galaxies has an environmental dependence. We focus on the passive central galaxies to ensure a like-to-like comparison in determining how their central and satellite status affects their stellar population gradients. We use the SAMI spectroscopic classifications presented in Owers et al. (2019) to select a homogeneous sample. The galaxies are classified as star-forming, passive, or H$\text{\textsc{ii}}$-strong using the absorption and emission line properties of each SAMI spectrum. We select 843 passive galaxies; of these, 98 are central and 745 are satellite galaxies (Figure 1).

To ensure the stellar population measurements we use are reliable, we exclude all galaxies with masses less than $\log_{10}(M_\star/M_\odot) = 9.5$, owing to the low signal-to-noise ratio (S/N) and completeness of these galaxies (we note that selecting galaxies with $\log_{10}(M_\star/M_\odot) > 10$ does not change the conclusions we draw). This leaves 819 galaxies (98 central and 721 satellite galaxies). This excludes 40 nonpassive central galaxies with $\log_{10}(M_\star/M_\odot) > 9.5$. The median halo mass of the nonpassive central galaxies is $M_{200} = 10^{11.3} M_\odot$.

We also make a quality cut in S/N and velocity dispersion. For each galaxy, we only use the annular measurements that have $S/N \geq 10$ and velocity dispersions ($\sigma$) between 75 and 400 km s$^{-1}$. The [$\alpha/Fe$] measurements were also restricted to annuli with $S/N \geq 20$ owing to the greater uncertainties associated with measuring this parameter.

We select galaxies that have at least one annular measurement between 0.1 and 1 $R_e$ and at least three in total, all meeting the $S/N$ and $\sigma$ criteria, in order to probe similar spatial regions for our sample of galaxies. This is due to some of the satellite galaxies having effective radii $<1''1$–$1''2$, such that the first aperture probes radii greater than 1 $R_e$. This radial criterion is the primary source of exclusion for our sample.

These selection criteria result in a final sample of 533 galaxies with metallicities and age gradients (96 central galaxies and 437 satellite galaxies) and 332 galaxies with [$\alpha/Fe$] gradients (79 centrals and 253 satellites).

The distribution of $g-i$ color with stellar mass for the galaxies selected is illustrated in Figure 1. Figures 2 and 3

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$^{12}$ http://www.aao.gov.au/science/software/2dfdr
illustrate the completeness of the selected sample. As shown, our sample is representative of the parent sample in stellar mass and halo mass, with 96% completeness for passive galaxies with \( \log(M_*/M_\odot) \geq 9.5 \).

2.3. Stellar Mass

Stellar masses are estimated from \( g \) and \( i \) magnitudes using an empirical proxy developed from GAMA photometry (Taylor et al. 2011; Bryan et al. 2015). For cluster galaxies, stellar masses are derived using the same approach (Owers et al. 2017).

The \( g \) and \( i \) magnitudes are taken from Sloan Digital Sky Survey (SDSS; York et al. 2000) images for GAMA galaxies and VLT Survey Telescope (VST) ATLAS (Shanks et al. 2015) and SDSS DR9 (Ahn et al. 2012) observations for cluster galaxies. The VST/ATLAS data were reprocessed as described in Owers et al. (2017).

2.4. Effective Radius

Circularized effective radii, \( R_e \), were determined by fitting a Sérsic profile to \( r \)-band images. For group galaxies, these radii are taken from the GAMA Sérsic catalog v0.7 (Kelvin et al. 2012), whereas for cluster galaxies, the \( R_e \), expressed as the radius of the major axis, are taken from Owers et al. (2019) and converted to a circularized radius using the axial ratio for each galaxy. For the galaxies that are in common, cluster galaxies’ \( R_e \) are consistent when measured from VST/ATLAS and SDSS/GAMA (Owers et al. 2019).

2.5. Halo Mass

We use the GAMA Galaxy Group Catalogue (G3C; Robotham et al. 2011) to define the galaxy groups in the GAMA regions. In this catalog, galaxies are grouped using an adaptive friends-of-friends algorithm, taking advantage of the high spectroscopic completeness of the GAMA survey (∼98.5%; Liske et al. 2015). Following the recommendation of Robotham et al. (2011), we use the “iterative center” as the center of our halo. This center is found through an iterative procedure: at each step, the \( r_{AB} \)-band luminosity centroid of the halo is found and the most distant galaxies are rejected. When only two galaxies remain, the brightest is taken as the central galaxy.

For the GAMA groups, we use the halo mass, \( M_{200} \), the mass contained within \( R_{200} \) (the radius at which the density is 200 times the critical density; White 2001), calculated from the GAMA group velocity dispersion and calibrated using halos from simulated mock catalogs (see Robotham et al. 2011). The cluster halo masses are taken from Owers et al. (2017), who calculated them from a caustic analysis of the galaxy velocities and their distance from the cluster center.

It is important to note that, following Owers et al. (2017), we apply a scaling factor of 1.25 to the cluster halo masses to be consistent with the GAMA halo masses. We also scale the GAMA halo masses (\( H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1} \)) to be consistent with the cosmology used here.
2.6. Central Galaxies

We define the halo central galaxy as the most massive galaxy within 0.25 $R_{200}$ (e.g., Oliva-Altamirano et al. 2017). To identify the central galaxies for the group sample, we check that the galaxy identified as “iterative central” (Robotham et al. 2011) is also the most massive galaxy. This is true for 188/205 groups in our sample. Seventeen groups have different galaxies selected as the iterative central and most massive. For these 17 groups, we find the most massive galaxy within a radius of 0.25 $R_{200}$. For most of the groups (12/17), the most massive galaxy within 0.25 $R_{200}$ is the iterative central galaxy. For the five groups where another galaxy is found to be the most massive within 0.25 $R_{200}$, we select that galaxy as the central galaxy.

A similar procedure is carried out to select the central galaxy in the clusters in order to ensure consistency between the samples. We identify the galaxy that sits closest to the center of the cluster (cluster centroids are taken from Owers et al. 2017), as well as the most massive galaxy in the cluster. For three out of eight clusters, these galaxies are the same. For the other five clusters, we find the most massive galaxy within a radius of 0.25 $R_{200}$. For two clusters, this galaxy is also the central one, whereas for three out of five clusters (A168, A2399, and A4038), the most massive galaxy within 0.25 $R_{200}$ is not the galaxy closest to the center. This is consistent with the dynamical state of these clusters as discussed in Brough et al. (2017) and Owers et al. (2017). We therefore select the most massive galaxy within 0.25 $R_{200}$ as the central galaxy for these clusters.

2.7. Data

We use data from the SAMI v0.11 internal data release (reduced identically to DR2; Scott et al. 2018). This data release consists of 3071 galaxies, with repeat observations available for 277 galaxies.

Out of 3071 SAMI galaxies, 3019 have several annular measurements (up to four) of age, metallicity, and $\alpha$-element abundance ratio (and their corresponding errors). These are made in elliptical apertures centered on the center of the cube, with constant spacing along the major axis. The position angle, PA, and ellipticity, $\epsilon$, of the galaxy are determined using the find galaxy Python routine of Cappellari (2002) from the image generated by summing the cube along its wavelength axis. The spectra of each of the spaxels in each aperture are summed, and the resulting spectrum is analyzed in order to extract the stellar population measurements for each annular aperture.

2.8. Annular Stellar Population Measurements

Stellar population measurements were determined as described in Scott et al. (2017) using an approach based on Lick absorption line strengths. We summarize the method here and identify the differences Scott et al. (2018) took for aperture measurements compared to the total measures presented in Scott et al. (2017).

The Lick indices used for this analysis consist of indices defined by Worthey & Ottaviani (1997) and Trager et al. (1998): Balmer lines (H$\delta_A$, H$\delta_F$, H$\gamma_A$, H$\gamma_F$, and H$\beta$), iron-dominated lines (Fe4383, Fe4531, Fe5015, Fe5270, Fe5335, and Fe5406), molecular indices (CN1, CN2, Mg1, and Mg2), and Ca4227, G4300, Ca4455, C4686, and Mg$b$. All of these indices are in the SAMI blue wavelength range.

Before measuring the absorption line strength in the annular spectra, emission from star formation was removed by comparing the observed spectra with synthetic spectra unaffected by star formation. The best-fitting model was found using the penalized Pixel Fitting (pPXF) code of Cappellari & Emsellem (2004). This was done by fitting each spectrum with a set of 30 stellar template spectra chosen from the MILES library (Sánchez-Blázquez et al. 2006; Falcón-Barroso et al. 2011). The fit was performed for each input three times: the first run determines the noise in the spectra, the second run identifies bad pixels and emission-affected pixels, and the third fit replaces those pixels with the values of the best-fitting emission-free spectra (see Scott et al. 2017 for details). This replacement method is more robust than the simple subtraction of emission lines from the spectra, especially in cases of low continuum $S/N$ or weak emission or in the wings of emission lines.

In order to measure the Lick indices, all annular spectra were then broadened (by convolving with a Gaussian) in order to match the Lick resolution of the relevant index, also taking into account the combined instrumental broadening, intrinsic broadening due to the galaxy’s velocity dispersions, and additional broadening due to binning over many spaxels. For every index, a Monte Carlo procedure was used to estimate the uncertainties: noise was randomly added to the best-fitting spectrum, the indices were remeasured for 100 different realizations, and the standard deviation thus found was adopted as the error on each index (see Scott et al. 2017 for more details).

The indices measured were then converted into single stellar population (SSP) equivalent age, metallicity, and $\alpha$-element abundance through comparison with stellar population models that predict Lick indices as a function of logarithmic age, metallicity, and [$\alpha$/Fe]. For the SAMI galaxies, two different models were used: Schiavon (2007, hereafter S07) and Thomas et al. (2011, hereafter TMJ). These models were interpolated to a fine grid (with a resolution of 0.02 in [Z/H] and log age and 0.01 in [$\alpha$/Fe]). A $\chi^2$ minimization approach (first implemented by Proctor et al. 2004) was used to find the SSP that best reproduced the indices measured. As described in Scott et al. (2017), this also iteratively excluded indices if they were more than $1\sigma$ outside the range covered by the model. Moreover, the fit would not return a solution if the fitted indices did not include at least one Balmer index and at least one Fe index. A robust estimation of $\alpha$-element abundance was not always possible due to the S/N of the spectra ($S/N < 20$). The absorption lines corresponding to the relevant indices were sometimes too shallow or not broad enough to be detected at a high enough S/N.

For each spectrum, the values of age, [Z/H], and [$\alpha$/Fe] were taken from the minimum $\chi^2$ fit, and their uncertainties were determined from a $\chi^2$ distribution in the 3D space of the three parameters.

Comparing the stellar population parameters found with the two models, a good agreement is found for [Z/H] and [$\alpha$/Fe] (although the latter presents a small offset between the two models). The poorest agreement is found comparing ages from the two models, with TMJ predicting older ages. The broad scatter is the result of the fact that the stellar populations are luminosity-weighted; therefore, the equivalent mean ages are more sensitive to the youngest populations. The TMJ model predicts older ages at a given H$\beta$ because several galaxies have
Balmer line indices that lie outside the TMJ model grid (Kuntschner et al. 2010); therefore, the age measurements at low metallicities found by this model are not reliable. After considering all of these factors, Scott et al. (2017) adopted the S07 model to derive SSP-equivalent ages, while the TMJ model was used to derive the [Z/H] and [α/Fe] values as a best compromise given the limitations, noting that neither model perfectly describes the full set of indices in the SAMI sample. We found that this approach produced good agreement with previous literature studies, whereas the TMJ ages showed an unphysical upturn to much older ages at low masses/metallcities. However, our work focuses on relative age differences, not absolutes. Considering that relative ages are more accurate, and that the galaxies in the sample presented here do not reach the low metallicities where age reliability is problematic, our results are robust against this issue.

3. Analysis

3.1. Derived Gradients

A log–log linear fit is applied to the annular stellar population measurements of each galaxy using the Python package scipy.optimize.curve_fit (Virtanen et al. 2020) in order to derive the corresponding stellar population gradient. The fit takes into account the errors from the stellar population measurements and uses nonlinear least squares to fit a straight line to the data. For the age measurements, since the age uncertainties are asymmetric, we fit the gradient using the mean error on each point.

The fitted slope is taken as the gradient, and the uncertainty on the gradient is derived using a Monte Carlo procedure, where each annular value is randomly taken in their uncertainty window and the linear fit is applied again (with the errors taken into account) for 1000 different realizations. The standard deviation from the mean value of the slope is then taken as the uncertainty on the gradient derived.

We note that, as pointed out by Oyarzún et al. (2019), a nonlinear fit could be a better model when derivingGoing toward the outskirts of the galaxy. However, having only three to four radial bins for galaxies in our sample, a linear fit with logarithmic radius is the most robust solution. We also note that choosing to fit the gradients up to 1 $R_e$ instead of to the last available radial bin does not change the conclusions we draw.

We do not take the inclination of the galaxies into account when deriving the gradients, consistent with previous studies (e.g., Greene et al. 2015; Oliva-Altamirano et al. 2015; Goddard et al. 2017; Zheng et al. 2017; Ferreras et al. 2019).

In order to consider the effects of seeing on our results, we compared the half-width at half-maximum (HWHM) of the point-spread function (PSF) with the effective radius and the first and last radial bins available, as shown in Figure 4. Some of the gradients may be strongly affected by the PSF width, since it is significant compared to the galaxy size (six galaxies out of 533 have $R_e < $PSF).

To measure the effect of the PSF width on the derivation of the gradients, we first analyze the radial profiles of the 23 galaxies in our final sample that have multiple observations available. A small number of the repeat observations exhibit small-scale variations in the flux (alasing; see Green et al. 2018 for an extended discussion) that can affect the measured indices and therefore the derived population parameters. In such cases, we identify the discrepant observation by eye, selecting the cube with the more physical spectral variations. For the remaining 35 galaxies with repeated observations, we measure the slope of the best fit for each observation, finding a mean change in metallicity gradient of $\Delta[Z/H] = -0.03 \pm 0.05$. Figure 5 shows that, within the uncertainties, the measurements are consistent for the majority of the galaxies and show no trend with seeing. However, a more detailed analysis that accounts for the PSF is required to extract robust gradients with meaningful error bars.

Following Ferreras et al. (2019), we derive the gradients of each galaxy by fitting the observed population parameters in each radial bin to a linear function model convolved with the PSF of the observation. From this model, stellar population values are extracted in the same radial bins used for the observed values and compared with the original observations, applying a standard likelihood function. The best-fit parameters...
for the slope and the intercept of the linear model are then retrieved (with corresponding uncertainties) using a Markov Chain Monte Carlo sampler (EMCEE; Foreman-Mackey et al. 2013). More details on this process can be found in Ferreras et al. (2019).

The gradients derived following this method are in general steeper than those derived without taking into account the effect of the PSF width, due to the fact that the PSF tends to wash out the gradients. Figure 6 shows a radial metallicity profile of a typical galaxy with the gradient derived using both methods.

Example stellar population maps and radial profiles are shown in Figure B1 in Appendix B for two example galaxies (one central and one satellite galaxy). Hereafter, we refer to the gradients derived after correcting for the effect of the PSF. However, considering the gradients derived without taking into account the effect of the PSF does not change the conclusions we draw.

We explore the consequences that active galactic nuclei (AGN) could have on our results in Appendix C, finding that there is no significant influence from AGN emission on our stellar population measurements.

4. Results

In this section, we present the results we obtain for the stellar population gradients of passive central and satellite galaxies in the SAMI Galaxy Survey. Figures 7–9 show the binned gradients (metallicity, log age, and $\alpha$-element abundance ratio) as a function of stellar mass. To better understand and visualize any trends underlying these gradients, we group the gradients together by stellar mass in bins of 25 galaxies each for the central galaxies and 90 for the satellite galaxies in the plots showing age and metallicity gradients. We use bins of 20 galaxies for centrals and 70 galaxies for satellites for [$\alpha$/Fe] gradients.

Figure 7 shows that the metallicity gradients are negative and generally shallow ($\Delta[Z/H]/\Delta \log(r/R_e) \gtrsim -0.3$) at all masses. To test whether there is any statistically significant trend with mass for the whole sample, we use the Kendall’s correlation coefficient $\tau$ using the Python package scipy.stats.kendalltau (Virtanen et al. 2020). This correlation coefficient is robust to small sample sizes. A $\tau$ value close to 1 indicates strong agreement, while a value close to −1 indicates strong disagreement. We find a value of $\tau = 0.05$, with a probability of correlation of 93.8%. This suggests the possibility of a weak trend that the gradients tend to be shallower (less negative) with increasing mass.

Figure 8 shows that age gradients are slightly positive, showing no trend with stellar mass ($\tau = -0.02$, with a probability of correlation of 60%) and no difference in trend between central and satellite galaxies.

Figure 9 shows that [$\alpha$/Fe] gradients are consistent with zero and show a weak negative trend with stellar mass ($\tau = -0.13$, with a probability of correlation of 99.96%) and no difference between the different environments.

The mean gradient values for central and satellite galaxies are given in Table 1. The gradients for central and satellite galaxies are consistent within 1$\sigma$.

In order to test whether the scatter in the observed relations is due to measurement errors or an underlying intrinsic scatter, we use the LtsFit Python package, implementing the method used in Cappellari et al. (2013). This package performs a linear regression that allows for intrinsic scatter and observational errors in all coordinates. We applied this test to the subsets of central and satellite galaxies separately and to the whole sample. We found no evidence of a statistically significant intrinsic scatter for any of the observed relations.

4.1. Host Halo Mass Dependence

In order to determine whether there is any dependence of the gradients on host halo mass, we split our central galaxy sample into three subsets of halo mass. Each subset has an equal number of galaxies (32 galaxies for metallicity and age gradients and 26 galaxies for [$\alpha$/Fe] gradients). We then bin the satellite galaxies into the same halo mass subsets as the central galaxies.

Figure 10 shows the stellar population gradients of central and satellite galaxies as a function of stellar mass in the low
halo mass \((10.96 < M_{200} < 13.28)\) and high halo mass \((13.77 < M_{200} < 15.29)\) subsets. Each subset has been grouped into bins by stellar mass (similar to the mass bins described at the beginning of Section 4) to better visualize any underlying trend with stellar mass.

The metallicity gradients of central and satellite galaxies show no differences between those in low- and high-mass halos. In the stellar mass bins where we have values for both central and satellite galaxies, the metallicity gradients are negative and shallow for both central and satellite galaxies.

Age gradients are generally positive for both central and satellite galaxies, with no trend with stellar mass regardless of the host halo mass.

Central and satellite galaxies show similar \([\alpha/Fe]\) gradients for both environments.

5. Discussion

Due to its ability to map stellar populations across galaxies, IFS has been used as a valuable tool to explore the stellar population parameters of galaxies. Here we have analyzed the stellar population gradients of 533 passive galaxies from the SAMI Galaxy Survey. Of these, 96 are central galaxies, and 437 are satellite galaxies.

5.1. Metallicity Gradients

We observe shallow metallicity gradients in our sample (mean \(\Delta[Z/H] / \Delta \log(r/R_*) = -0.25 \pm 0.02\) with a 1σ deviation of 0.24 for central galaxies and mean \(\Delta[Z/H] / \Delta \log(r/R_*) = -0.30 \pm 0.01\) with a 1σ deviation of 0.24 for satellite galaxies). These are in agreement with previous results from Kuntschner et al. (2010) and Oliva-Altamirano et al. (2015).

Examining the relationship of metallicity gradients with stellar mass (Figure 7), we find a potential weak positive trend...
such that gradients are shallower (less negative) with increasing stellar mass. This is in agreement with Zheng et al. (2017), who found evidence of a weak positive trend of metallicity gradients with stellar mass, so that the gradients become less negative with increasing stellar mass, in a sample of 577 early-type MaNGA galaxies. Their trend is more evident when examining galaxies in low-mass halos (sheet and void environment).

However, we do not observe a transition to a shallower metallicity gradient at log$_{10}(M_*/M_\odot) = 10.54$, as observed by Kuntschner et al. (2010) and predicted by Taylor & Kobayashi (2017) from chemodynamical simulations.

Our lack of significant correlation with stellar mass is in contrast to Li et al. (2018), who found a clear decrease of the metallicity gradients (i.e., more positive gradients) with increasing stellar mass, and Goddard et al. (2017), who found a weak negative correlation of gradients with stellar mass in a sample of MaNGA ETGs. However, we note that if we examine the gradients derived by Goddard et al. (2017) and Li et al. (2018) for galaxies in the same mass range as those in our sample (9.5 < log$_{10}(M_*/M_\odot) < 11.8$), they show no strong dependence with stellar mass, in agreement with our results.

Tortora & Napolitano (2012), in a sample of about 4500 SDSS ETGs, found that age and metallicity gradients generally do not depend on environmental density, in agreement with our results. However, they found a residual dependence of metallicity gradient with environment for central galaxies (shallower metallicity gradients in denser environments).

### Table 1

|                      | Central Galaxies (1σ) | Satellite Galaxies (1σ) |
|----------------------|-----------------------|-------------------------|
| Δ[Z/H]/Δ log(r/R_e)   | -0.25 ± 0.02 (0.24)   | -0.30 ± 0.01 (0.24)     |
| Δ(log Age)/Δ log(r/R_e) | 0.13 ± 0.03 (0.33)   | 0.17 ± 0.01 (0.29)      |
| Δ[α/Fe]/Δ log(r/R_e)  | 0.01 ± 0.03 (0.23)    | 0.08 ± 0.01 (0.18)      |

**Note.** Uncertainties shown are errors on the mean. The 1σ deviations are shown in parentheses.

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**Figure 9.** [α/Fe] gradients as a function of stellar mass. All point types are the same as in Figure 7. [α/Fe] gradients are consistent with zero for both central and satellite galaxies. We find a weak trend of the gradients with stellar mass.

**Figure 10.** Median values of the metallicity gradients as a function of stellar and halo mass. Gradients for central galaxies are shown as pink squares (low-mass halos) and purple crosses (high-mass halos). Gradients for satellites are shown as light blue squares (low-mass halos) and dark blue crosses (high-mass halos). The uncertainties shown on the binned gradient values are the 25th and 75th percentiles in each bin. The dotted line represents a flat gradient. Metallicity gradients for central and satellite galaxies are negative and consistent within the errors for different halo masses. The metallicity gradients of galaxies in low-mass halos (both satellite and central galaxies) become shallower with increasing stellar mass compared to the gradients of galaxies in denser environments, which do not show any trend with stellar mass. The age gradients are generally positive for both central and satellite galaxies, with no differences between low- and high-mass halos. The [α/Fe] gradients are generally consistent with zero for both central and satellite galaxies and show no dependence on host halo mass.
Ferreras et al. (2019) made independent stellar population measurements for 522 ETGs in the SAMI Galaxy Survey and found a marginal steepening of metallicity gradient with increasing stellar mass. They found the steepening to be stronger in the denser cluster environments, whereas the group environments appear to have shallower metallicity gradients. While we do not see a steepening in the metallicity gradients in denser environments, Ferreras et al.’s (2019) mean gradients are consistent with our derived gradients, as shown in Figure 7 (lower panel), and the relationships are consistent within their errors. The difference in the metallicity gradient–stellar mass relationship observed by Ferreras et al. (2019) could therefore be driven by the different selection of halo structures.

5.2. Age Gradients
We find mildly positive age gradients (i.e., younger centers) with mean \( \Delta \log (\text{Age/Gyr})/\Delta \log (r/R_e) = 0.13 \pm 0.03 \) for central galaxies and mean \( \Delta \log (\text{Age/Gyr})/\Delta \log (r/R_e) = 0.17 \pm 0.01 \) for satellite galaxies with 1\( \sigma \) deviations of 0.33 and 0.29, respectively.

Evidence of flat or slightly positive gradients in age has been previously observed by numerous studies, such as Sánchez-Blázquez et al. (2007), Brough et al. (2007), Kuntschner et al. (2010), Loubser & Sánchez-Blázquez (2012), Greene et al. (2015), and Goddard et al. (2017).

We find no correlation of age gradients with stellar mass, in agreement with Zheng et al. (2017).

Ferreras et al. (2019) found that there is a slight steepening of the age gradients toward high-mass galaxies (with a slope of \(-0.07 \pm 0.04\)); in particular, galaxies in groups appear to have steeper age gradients (i.e., more negative) than galaxies in clusters, as shown by the red and gray lines in Figure 8 (lower panel). When examining our sample as a function of halo mass, we do not see any trend of age gradient with stellar mass or any dependence on halo mass (in agreement with Tortora & Napolitano 2012). While our relationships are not consistent with Ferreras et al. (2019), their mean gradients are consistent with our derived gradients, as shown in Figure 8. The difference in relationship is likely driven by the different selection of low- and high-mass halos for the analysis (Ferreras et al. 2019 divided galaxies into group versus cluster galaxies).

5.3. \([\alpha/Fe]\) Gradients
We find flat and shallow \([\alpha/Fe]\) gradients with a mean value of \( \Delta \log \alpha/Fe/\Delta \log (r/R_e) = 0.01 \pm 0.03 \) for central galaxies and \( \Delta \log \alpha/Fe/\Delta \log (r/R_e) = 0.08 \pm 0.01 \) for satellite galaxies with standard deviations of 0.23 and 0.18, respectively. These results are in good agreement with Kuntschner et al. (2010), who found \( \Delta \log \alpha/Fe/\Delta \log (r/R_e) \) between 0.01 and 0.07.

We find a weak negative correlation of \([\alpha/Fe]\) gradients with stellar mass, such that the gradients are more negative with increasing masses (Figure 9). Greene et al. (2015), with a sample of 50 MASSIVE galaxies and 50 lower-mass galaxies, found similar \([\alpha/Fe]\) gradients, but their correlation is opposite to that found here: galaxies in their low-mass bin (\(10.1 \lesssim \log_{10}(M_*/M_\odot) \lesssim 11.2\)) have \( \Delta \log \alpha/Fe/\Delta \log (r/R_e) = -0.09 \pm 0.06 \), and galaxies in their higher-mass bin (\(\log_{10}(M_*/M_\odot) > 16\)) have \( \Delta \log \alpha/Fe/\Delta \log (r/R_e) = 0.1 \pm 0.08 \). However, the gradients are consistent within our 1\( \sigma \) deviation.

Greene et al. (2019) found that \([\alpha/Fe]\) gradients for very high-mass galaxies (\(11.6 < \log_{10}(M_*/M_\odot) < 12.2\)) are consistent with zero, with a median value of \( \Delta \log \alpha/Fe/\Delta \log (r/R_e) = -0.03 \pm 0.02 \), in agreement with our median value for central galaxies, \( \Delta \log \alpha/Fe/\Delta \log (r/R_e) = 0.01 \pm 0.03 \).

Ferreras et al. (2019) found evidence of \([\alpha/Fe]\) gradients varying from positive to more negative with increasing mass for cluster galaxies (Figure 9), in agreement with what we see for central galaxies in high-mass halos. However, we do not see more negative \([\alpha/Fe]\) gradients for satellite galaxies in high-mass halos.

Similarly shallow positive \([\alpha/Fe]\) gradients are also found in simulations. Hirschmann et al. (2015) derived mildly positive age gradients (\(\Delta \log \text{(Age/Gyr)}/\Delta \log (r/R_e) \approx 0.04\)). Taylor & Kobayashi (2017) found small positive \([\alpha/Fe]\) gradients (\(\Delta \log \alpha/Fe/\Delta \log (r/R_e) \approx 0.1–0.2\)).

5.4. Implications
In this paper, we find negative metallicity gradients, positive age gradients, and flat \([\alpha/Fe]\) gradients. The metallicity gradients show evidence of a potential weak trend with stellar mass, so that gradients become less negative with increasing stellar mass, while \([\alpha/Fe]\) gradients become more negative with increasing mass. When examining the galaxies as a function of halo mass, we find evidence of shallower (less negative) metallicity gradients with increasing stellar mass for galaxies in low-mass halos but no significant difference between the gradients of central and satellite galaxies.

The gradients we find are consistent with those predicted for galaxies formed in a two-phase process (White 1980; Kobayashi 2004; Oser et al. 2010). In this scenario, galaxies first undergo a rapid formation phase during which “in situ” stars are formed within the galaxy. The more massive ETGs start forming stars at earlier epochs (de Lucia et al. 2006; Dekel et al. 2009). The resulting galaxy is compact, with a steep negative metallicity gradient (with gradients ranging from \(\Delta [Z/H]/\Delta \log (r/R_e) = -0.35\) to \(-1.0\); Kobayashi 2004) and a positive age gradient (due to the presence of a younger stellar population in the center of the galaxy). More specifically, the metallicity and age gradients would naturally correlate with galaxy mass, as star formation lasts longer in the center of more massive systems that have deeper central potential wells (e.g., Kobayashi 2004; Pipino et al. 2010), so more massive galaxies would have younger and more metal-rich centers, more positive age gradients, and more negative metallicity gradients.

After the star formation is quenched, a second phase of slower evolution is dominated by dissipationless mergers. In particular, galaxy interactions will either steepen or flatten the metallicity gradients; major dissipationless mergers tend to cause gradients to become shallower as metal-rich stars from the center of the galaxy are redistributed further out (Kobayashi 2004; di Matteo et al. 2009; Rupke et al. 2010; Navarro-González et al. 2013; Taylor & Kobayashi 2017), and minor dissipationless mergers lead to steeper negative metallicity gradients due to metal-poor stars being accreted in the outer regions from lower-mass galaxies (Hilz et al. 2012, 2013; Hirschmann et al. 2015).

Central galaxies, due to their privileged position in the center of the potential well, are expected to experience a greater number of galaxy interactions compared to satellite galaxies. In this scenario, simulations predict flat or slightly positive age gradients.
gradients due to old stars being added in the outer regions (at radii \( > 2 R_e \); Hirschmann et al. 2015), and \([\alpha/Fe]\) profiles are expected to be flat as a result of massive ETGs assembling via mergers with low-mass systems (Gü et al. 2018). These predictions are in agreement with our findings; the metallicity gradients we find (see Table 1) are shallower than those predicted by a monolithic collapse (ranging from \( \Delta [Z/H] / \Delta \log (r/R_e) = -0.5 \) (Carlberg & Freedman 1985) to \( \Delta [Z/H] / \Delta \log (r/R_e) = -1.0 \) (Kobayashi 2004)), hinting at a flattening of the gradients due to mergers. The age gradients are slightly positive (with central stars having younger ages than stars in the outskirts) and generally flat \([\alpha/Fe]\) gradients. However, since evidence of minor later accretions is expected at radii \( 1.5 < R < 2 R_e \), and the majority of the radial profiles for our central galaxies only extend to a maximum of \( 2 R_e \) (as shown in Figure 11), our results point to a similar evolution path for the inner regions of both central and satellite galaxies.

Previous works have seen clear evidence that satellite galaxies in these environments are found to be older than central galaxies of the same stellar mass in high-density environments (Thomas et al. 2005; Pasquali et al. 2010; la Barbera et al. 2014; Scott et al. 2017). However, we do not see a difference in the gradients of central and satellite galaxies when taking into account the mass of their host halos.

The fact that our metallicity gradients for central and satellite galaxies are consistent within the standard deviation suggests that the inner regions of central galaxies (up to \( 2 R_e \)) form in a similar fashion to similarly massive satellite galaxies. Moreover, the gradients for galaxies in high-mass halos show no trend with stellar mass. This seems to point to a similar evolution for galaxies in denser environments, regardless of their current position in the halo.

The potential trend of shallower metallicity gradients with increasing stellar mass in low-mass halos could point to a greater number of interactions in the group environment. Galaxy interactions in this environment are more likely due to the lower relative velocity at which galaxies are moving. In high-mass halos, the frequency of galaxy mergers is low due to the fast orbital motions of the galaxies and the long timescales for dynamical friction (e.g., Park & Hwang 2009).

The consistent stellar population gradients ([Z/H], age, and \([\alpha/Fe]\)) presented here for both central and satellite galaxies suggest a similar formation and evolution history for the inner regions \( (R < 2 R_e) \) of central and satellite galaxies, with no dependence on their host halo mass.

6. Conclusions

We have analyzed the stellar population radial profiles obtained from IFU observations of a large sample of passive galaxies (with \( 9.5 < \log_{10}(M_*/M_\odot) < 11.8 \)) spanning different environments in the SAMI Galaxy Survey. We have compared the derived gradients of central galaxies to those of satellite galaxies. Our final sample of passive galaxies consists of 533 galaxies, including 96 central and 437 satellite galaxies. The sample used for \([\alpha/Fe]\) analysis is smaller (332 galaxies) due to the higher S/N required. We draw the following conclusions.

1. The metallicity gradients found are negative \( \Delta [Z/H] / \Delta \log (r/R_e) = -0.25 \pm 0.03 \) for central galaxies and \( \Delta [Z/H] / \Delta \log (r/R_e) = -0.30 \pm 0.01 \) for satellites; Figure 7. There is evidence of shallower (less negative) metallicity gradients with increasing stellar mass.

2. Age gradients (Figure 8) are slightly positive \( \Delta \log (\text{Age/Gyr}) / \Delta \log (r/R_e) = 0.13 \pm 0.03 \) for centrals and \( \Delta \log (\text{Age/Gyr}) / \Delta \log (r/R_e) = 0.17 \pm 0.01 \) for satellites.

3. The \([\alpha/Fe]\) gradients are flat or slightly positive \( \Delta \alpha/Fe / \Delta \log (r/R_e) = 0.01 \pm 0.03 \) for centrals and \( \Delta \alpha/Fe / \Delta \log (r/R_e) = 0.08 \pm 0.01 \) for satellites. We find \([\alpha/Fe]\) gradients to have a weak negative correlation with stellar mass, showing more negative gradients with increasing mass (Figure 9).

4. The mean values of the gradients are consistent with a two-phase formation process. The metallicity gradients are shallower than the gradients expected from a pure dissipative collapse model (Table 1). The age and \([\alpha/Fe]\) gradients are consistent with those expected for galaxies where the contribution from subsequent accretion events is significant.

5. The stellar population gradients found for central galaxies are consistent with those found for satellite galaxies.

6. The stellar population gradients of central and satellite galaxies show no significant difference as a function of halo mass. We find metallicity gradients of galaxies in the low-mass halo bins to have a potential positive correlation with stellar mass, showing less negative gradients with increasing mass.

7. The lack of a significant difference with environment suggests that the stellar population gradients in the inner regions \( (r < 2 R_e) \) of passive galaxies have no significant dependence on their environment (Table 1). This result points to a similar formation and evolutionary history for the inner regions of central and satellite galaxies.

In order to further test the formation process of central galaxies and reach a clearer understanding of how these galaxies form and the main processes that influence their formation.
evolution, observations of their stellar population gradients at larger radii are needed.

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Appendix A

Radial Profiles of High-mass Central Galaxies

Three high-mass \((\log_{10}(M_*/M_\odot) > 11.4)\) central galaxies (two in clusters and one in the GAMA groups) are very large \((R_e > 25''\) compared to the 15'' diameter SAMI field of view. Though their measurements only cover a small portion of the galaxy, up to 0.26 \(R_e\), they still meet our selection criteria. We illustrate their radial metallicity profiles in Figure A1.

Appendix B

Stellar Population Maps

Example stellar population (metallicity, age, and \([\alpha/Fe]\)) binned maps and radial profiles are shown in Figures B1–B3 for two galaxies (one central and one satellite). Stellar population binned maps have been created specifically for these two examples and have not been used in this study.

Figure A1. Radial metallicity profiles of the three high-mass central galaxies with measurements only within 0.3 \(R_e\). We retain these galaxies in the final sample (we show their radial metallicity profiles for transparency).
Figure B1. Example metallicity maps and radial metallicity profiles for two typical galaxies: central and satellite. Radial profiles are color-coded as follows: purple for central galaxies and blue for satellite galaxies. Stellar mass is given in the bottom right corner of the first panel, $R_e$ is shown in the first panel as a dashed black circle, and PSF extent is shown in the radial profile as a green dotted line. The stellar metallicity decreases going toward the outskirts of the galaxy.

Figure B2. Example age maps and radial age profiles for two typical galaxies: central and satellite. Radial profiles are color-coded as follows: purple for central galaxies and blue for satellite galaxies. Stellar mass is given in the bottom right corner of the first panel, $R_e$ is shown in the first panel as a dashed black circle, and PSF extent is shown in the radial profile as a green dotted line.
Appendix C

AGN Contribution

Since AGN have strong, very bright emission lines in their centers that may bias stellar population fitting, we investigate the importance of this contribution by comparing gradients of a sample of galaxies that includes galaxies known to have AGN activity in the GAMA regions with non-AGN GAMA galaxies (168 galaxies with AGN out of 332 in our sample; Schaefer et al. 2017). As shown in Figure C1, there is no significant difference in the metallicity and age gradients between the two samples. We therefore conclude that there is no significant influence from AGN emission on our stellar population measurements and include all galaxies in our sample.
