Spatially resolved direct method metallicity in a high-redshift analogue local galaxy: temperature structure impact on metallicity gradients

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ABSTRACT
We investigate how H\textsc{i} region temperature structure assumptions affect “direct-method” spatially-resolved metallicity observations using multispecies auroral lines in a galaxy from the SAMI Galaxy Survey. SAMI609396B, at redshift $z = 0.018$, is a low-mass galaxy in a minor merger with intense star formation, analogous to conditions at high redshifts. We use three methods to derive direct metallicities and compare with strong-linediagnostics. The spatial metallicity trends show significant differences among the three direct methods. Our first method is based on the commonly used electron temperature $T_e$ ([O\textsc{i}]) from the [O\textsc{i}]/[O\textsc{iii}] auroral line and a traditional $T_e$([O\textsc{ii}]) calibration. The second method applies a recent empirical correction to the O$^+$ abundance from the [O\textsc{ii}]/[O\textsc{iii}] strong-line ratio. The third method infers the $T_e$([O\textsc{ii}]) from the [S\textsc{ii}] auroral lines. The first method favours a positive metallicity gradient along SAMI609396B, whereas the second and third methods yield flattened gradients. Strong-line diagnostics produce mostly flat gradients, albeit with unquantified contamination from shocked regions. We conclude that overlooked assumptions about the internal temperature structure of H\textsc{i} regions in the direct method can lead to large discrepancies in metallicity gradient studies. Our detailed analysis of SAMI609396B underlines that high-accuracy metallicity gradient measurements require a wide array of emission lines and improved spatial resolutions in order to properly constrain excitation sources, physical conditions, and temperature structures of the emitting gas. Integral-field spectroscopic studies with future facilities such as JWST/NIRSpec and ground-based ELTs will be crucial in minimising systematic effects on measured gradients in distant galaxies.

Key words: ISM: abundances – galaxies: abundances – galaxies: ISM – galaxies: fundamental parameters

1 INTRODUCTION

Abundances of heavy elements (metallicities) in the interstellar medium (ISM) of galaxies are enriched by stellar nucleosynthesis and trace star formation histories and gas-flow processes that ultimately shape the galaxy population. In particular, the spatial distribution of metallicity offers a powerful probe on the role of mergers, outflows, gas mixing, and gas accretion in transforming galaxies (e.g., Edmunds & Greenhow 1995; Kewley et al. 2010; Torrey et al. 2012; Magrini et al. 2016; Finlator 2017; Ma et al. 2017; Bresolin 2019; Tissera et al. 2019; Hemler et al. 2020). Spatial distributions of metals are often summarised as radial abundance gradients and azimuthal variations (e.g., Searle 1971; Vila-Costas & Edmunds 1992; Li et al. 2013; Ho et al. 2015, 2019), with both negative and flat metallicity gradients widely observed in the Milky Way and other local galaxies (e.g., Deharveng et al. 2000; Bresolin et al. 2004; Berg et al. 2013, 2020).

Spatially resolved studies of galaxies are now far more accessible compared to a decade ago, thanks to the advent of integral-field unit (IFU) spectroscopy. Multiplexed IFU surveys (e.g. CALIFA Sánchez et al. 2012; SAMI Bryant et al. 2015; MaNGA Bundy et al. 2015) have afforded large samples of gradient measurements in the local Universe. Studies find a dependence on stellar mass: low-mass...
galaxies ($\sim 10^9 M_\odot$) show almost flat gradients, with negative gradients steepening to high masses (Belliotre et al. 2017; Poetrodjojo et al. 2018). Spatially resolved measurements become more challenging at high redshift and observations show a substantial amount of scatter (Yuan et al. 2011; Jones et al. 2013; Leethochawalit et al. 2016; Carton et al. 2018; Wang et al. 2019; Curti et al. 2020b). One major caveat in using this broad range of observations to develop a coherent model of galaxy evolution is that different measurement techniques are often in disagreement.

A number of observational methods exist for determining the oxygen abundance (metallicity hereafter) of the ISM in galaxies from emission line spectroscopy (see Maiolino & Mannucci 2019; Kewley et al. 2019 for recent reviews). However, different techniques often show large offsets up to 0.7 dex (e.g. Kewley & Ellison 2008; Peimbert et al. 2017). This stark disagreement between different metallicity measurement techniques presents an ongoing challenge for studying chemical evolution of galaxies.

Emission line strengths in the photoionised nebulae around hot O- and B-type stars (H II regions) are sensitive to electron temperature ($T_e$), in addition to ionic abundances, ionisation parameter, and ISM pressure. Thus, a desirable approach to metallicity measurement is to use ratios of auroral emission lines and corresponding strong nebular emission lines to explicitly determine $T_e$, and subsequently metallicity (Direct Method; e.g., see Pérez-Montero 2017 for an overview). This “direct method” is traditionally considered the gold standard in abundance determination (e.g. Maiolino & Mannucci 2019), and underpins the calibration of many alternative techniques (e.g. Pettini & Pagel 2004; Curti et al. 2020a). However, one major practical issue with the direct method is that the faintness of the optical auroral lines severely limits its application. An alternative $T_e$-based method outlined by Jones et al. (2020) determines oxygen abundance based instead on far-infrared oxygen lines ($[\text{O} \, \text{III}] 85\mu$m or $[\text{O} \, \text{II}] 88\mu$m). This is expected to be favourable beyond $z \geq 5$ where these far-IR features can be observed with millimeter instruments such as ALMA, but is difficult to apply at lower redshifts.

Due to the faintness of auroral lines required for the direct method, strong-line methods are widely adopted in observations. Strong-line methods use ratios of the brightest rest-frame ultra-violet and optical emission lines to empirically determine the metallicity with calibrations based on either direct-method observations (e.g. Pettini & Pagel 2004; Pilyugin & Thuan 2005; Curti et al. 2020a) or stellar population synthesis and photoionisation models (e.g. Kewley & Dopita 2002; Kobulnicky & Kewley 2004; Dopita et al. 2016). Strong-line methods vastly expand the redshift and mass range of galaxies for which metallicities can be derived. However, it has been widely observed that metallicities measured with different methods often disagree (e.g. Kewley & Ellison 2008; Moustakas et al. 2010; Morales-Luís et al. 2014). In particular, theoretical methods, are reliant on simple geometries, such as spherical or plane parallel, and assume a constant temperature, constant density, or a constant pressure.

Despite the baseline role of the direct method, it does have limitations beyond practical detection-rate issues (Nicholls et al. 2020; Yates et al. 2020). H II regions are complex structures and summarising their conditions with integrated measurements of emission line ratios carries many assumptions. For example, H II regions are known to have internal temperature variations (Peimbert 1967; Kewley et al. 2019). An observed emission line ratio samples the luminosity-weighted average conditions of the emitting nebulae (Nicholls et al. 2020). The direct method is best applied by constructing a multi-zone temperature model using auroral lines from multiple ionic species (e.g. Pérez-Montero 2017; Berg et al. 2020). Commonly used auroral lines include those from O$^{-2}$, O$^{-}$, N$^{+}$ or S$^{2+}$ ions. This allows internal temperature gradients to be sampled since ions with differing ionisation energies preferentially sample different sub-regions of the nebulae.

However, measuring auroral lines from multiple species in observations presents a difficult practical challenge. Even detection of a single auroral line, commonly $[\text{O} \, \text{II}] 4363$, is generally considered a favourable outcome. But since the $[\text{O} \, \text{II}] 4363$ line is only produced in the hottest regions of a nebula, a resulting $T_e$-derived metallicity may be a lower limit to the true metallicity if there is a temperature gradient (Kewley et al. 2019). To overcome the lack of direct constraints on the multi-zone temperature structure, abundance measurements are often made adopting empirical relations between temperatures from different ions. For example, the $[\text{O} \, \text{II}]$ temperature ($T_e([\text{O} \, \text{II}]$)) is indirectly inferred from the $[\text{O} \, \text{I}]$ temperature ($T_e([\text{O} \, \text{I}]$)); based on $[\text{O} \, \text{II}] 4363$ using the $T_e([\text{O} \, \text{I}]$) – $T_e([\text{O} \, \text{II}]$) relation (e.g. Izotov et al. 2006; López-Sánchez et al. 2012; Pérez-Montero 2017). Recently, Yates et al. (2020) show that at low $O^{+}/O^{+}$, this approach can lead to large deficits in the measured $O^{+}$ abundance, causing total oxygen abundances to be underestimated by up to ~0.6 dex.

Studying metallicity in spatially resolved detail exacerbates the practical limitations of the direct method. Indeed, direct method metallicities have been mapped only for the Milky Way and small samples of large nearby spiral galaxies (Deharveng et al. 2000; Bresolin et al. 2004; Li et al. 2013; Berg et al. 2013, 2015, 2020; Croxall et al. 2015, 2016; Ho et al. 2019), exploring only a very narrow subset of the galaxy population. Here we leverage public release IFU data from the SAMI Galaxy Survey to expand spatially resolved direct method metallicity measurements to a new parameter space. From a search of auroral lines in SAMI Data Release 2 data cubes, we identify one particularly strong candidate: SAMI609396. This target is a minor-merger system and one galaxy in the system (SAMI609396B) is experiencing a burst of star formation. SAMI609396B is analogous to a high-redshift galaxy given its low-mass and high SFR. We detect prominent, spatially resolvable emission of three auroral lines: $[\text{S} \, \text{II}] \lambda 4069, 76, [\text{O} \, \text{II}] 4363$ and $[\text{S} \, \text{III}] \lambda 4632$ in SAMI609396B. In this contribution, we focus on this notable case to study direct method metallicity and electron temperature in a spatially resolved manner. The presence of auroral lines from multiple ionic species allows us to investigate the common assumption of using an assumed temperature relation (e.g. $T_e([\text{O} \, \text{II}]$) – $T_e([\text{O} \, \text{I}]$) relation) on the spatial distribution of metallicity in galaxies. Additionally, comparisons to strong-line metallicity trends provide further insight into possible systematic effects in samples of gradients measured in the local and high-redshift Universe. Given the rarity of spatially resolved $T_e$ studies at low redshift, and the relevance of this object to high-redshift comparisons, it warrants a detailed study of its own.

This work is organised as follows. In Section 2 we briefly describe the SAMI DR2 public release data, general properties of the SAMI609396 system, and selection of SAMI609396B. Our methodology for deriving spatially resolved electron temperature measurements is outlined in Section 3. In Section 4 we derive metallicity maps from three different “direct method” approaches and four different strong-line methods and discuss the differences in spatial trends favoured by each. We discuss further caveats in Section 5 be-

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1. The Cl$^{+2}$ and Ar$^{+3}$ ions can provide similar temperature probes to complement O$^{+2}$ measurements, however are usually too faint to be detectable.
fore summarising and presenting conclusions in Section 6. Detailed descriptions of the derivation of global properties, spectral fitting and emission line measurements are deferred to the Appendix. We also include a list of SAMI galaxies with visibly identifiable auroral line emission in the Appendix. Throughout this paper we adopt the Planck Collaboration et al. (2016) cosmology: \( \Omega_{\Lambda} = 0.692, \Omega_M = 0.308, \sigma_8 = 0.815, \) and \( H_0 = 67.8 \, \text{km s}^{-1} \, \text{Mpc}^{-1}. \) All magnitudes are quoted in the \( AB \) magnitude system (Oke & Gunn 1983).

2 THE SAMI GALAXY SURVEY

We conducted a search for auroral lines in SAMI Galaxy Survey Public Data Release 2 \(^2\) (Bryant et al. 2015; Green et al. 2018; Scott et al. 2018). The SAMI Galaxy Survey (Bryant et al. 2015) is a large IFU survey targeting low-redshift \((z \leq 0.1)\) galaxies with the Sydney – Australia Astronomical Observatory Multi-Object Integral Field Spectrograph (Croom et al. 2012). Reduced SAMI data cubes are formed by sampling dithered hexabundle observations onto a regular grid (refer to Allen et al. 2015 and Sharp et al. 2015 for details).

The SAMI aperture of radius is approximately \(~7.5 \arcs\) with a sampling of \(0.5 \times 0.5 \arcs\) spaxels. The true spatial resolution is limited by the seeing, recorded as FWHM_\text{PSF} = 2.07 \arcs (\sim 790 \, \text{pc}) for SAMI609396. SAMI observes in two spectral bands. The blue arm covers the observed wavelength range from 3750–5750 Å at low spectral resolution (\(R \sim 1808, \sigma_{V} \sim 74 \, \text{km s}^{-1}, \) at 4800 Å), while the red arm covers from 6300–7400 Å at medium resolution (\(R \sim 4304, \sigma_{V} \sim 29 \, \text{km s}^{-1}, \) at 6850 Å) (e.g., Zhou et al. 2017). For more detailed information on the SAMI survey and data products, the reader is referred to the above references.

Among nine SAMI galaxies in which we visually identified the presence of up to three auroral lines \((\text{[S}\,\text{n}]\lambda 4606.9, 76, \, \text{[O}\,\text{n}]\lambda 4363, \, \text{and [S}\,\text{n}]\lambda 6312)\), we highlight one notable case, SAMI609396 – a minor-merger system (Figure 1). The remainder of this paper is focused on this object. The list of SAMI galaxies we compiled with identifiable auroral line emission can be found in Appendix A.

2.1 SAMI609396

SAMI609396 (SDSS J114212.25+002004.0) is identified as a minor merger in the Sloan Digital Sky Survey (SDSS) images (Figure 1). The two merging galaxies are not deblended in the SDSS catalog with the merger system having a total \(r\)-band magnitude of 13.95. The SAMI input catalog gives the heliocentric redshift as \(z = 0.01824.\)

The merger signatures are evident from the colour difference and tidal tails. A visual inspection of the system shows one smaller galaxy exhibiting a strong blue colour, with a larger companion that is significantly redder (see Figure 1 middle panel). Spatially-resolved 1D spectra from the publicly available SAMI datacube show that the smaller galaxy in this system (SAMI609396B) is experiencing a burst of star formation associated with strong \([\text{O}\,\text{n}]\lambda 5007\) emission lines (Equivalent Width (EW) \(~200 \, \text{A})\). Several prominent auroral emission lines \((\text{[S}\,\text{n}]\lambda 4606.9, 76, \, \text{[O}\,\text{n}]\lambda 4363, \, \text{and [S}\,\text{n}]\lambda 6312)\) are detected in SAMI609396B. Using spatially resolved star formation rate (SFR) maps and photometry from SAMI (Appendix B), we derive SFR and \(M_\star\) estimates for SAMI609396B of \(4.21 \pm 0.30 \, M_\odot \, yr^{-1}\) and \(\log(M_\star/M_\odot) = 9.18 \pm 0.05.\) These values of SFR and \(M_\star\) place SAMI609396B 1.3 dex above the local star formation ‘main-sequence’ (Renzini & Peng 2015).

2.1.1 SAMI609396B properties in the context of high-redshift galaxies

A number of galaxy properties have been shown to evolve systematically with redshift including SFR (e.g. Speagle et al. 2014), metallicity (e.g. Zahid et al. 2013; Sanders et al. 2020), ionisation parameter (Sanders et al. 2016), and nebular emission line ratios (e.g. Kewley et al. 2013; Steidel et al. 2014). Given that placing observational constraints on high-redshift galaxies is comparably much more challenging than for local galaxies, there has been interest in obtaining observational constraints for “high-redshift analogues” (e.g. Heckman et al. 2005; Cardamone et al. 2009; Green et al. 2014; Bian et al. 2016). These are galaxies at low-redshift with properties that emulate those observed in high-redshift galaxies. Given the rarity of auroral emission lines in IFU data, we consider that SAMI609396B is worthy of a detailed study on its own. However, we also consider how its properties compare to those seen in high-redshift galaxies.

As outlined above in §2.1, the SFR and \(M_\star\) measurements for SAMI609396B are more than 1 dex above the local star-forming main sequence, more in line with values typical of galaxies at \(z \geq 1.\) Global metallicity correlates positively with stellar mass at \(z \sim 0\) (Mass-Metallicity Relation; refer to Maiolino & Mannucci 2019 and references therein), and at fixed stellar mass, metallicity is seen to decrease with increasing redshift (Zahid et al. 2013; Sanders et al. 2020). According to a recent multi-diagnostic determination by Sanders et al. (2020), galaxies of a mass comparable to SAMI609396B \((M_\star/M_\odot \sim 9.18)\) would have a median metallicity of \(12+\log(O/H) = 8.55\) at \(z \sim 0, 12+\log(O/H) = 8.26\) at \(z \sim 2.3,\) and \(12+\log(O/H) = 8.17\) at \(z \sim 3.3.\) Absolute metallicity values for individual galaxies are notoriously difficult to determine and depend strongly on the calibration used (e.g. Kewley & Ellison 2008). Although we do not take the step of applying the same metallicity calibration used by Sanders et al. (2020), according to the metallicities we derive for SAMI609396B in §4 we expect that the metallicity of SAMI609396B would likely fall somewhere between the median values expected from the \(z \sim 0\) and \(z \sim 2.3\) samples.

Ionisation parameters and electron densities in \(z \sim 2.3\) galaxies have been shown to be systematically offset from local galaxies at fixed stellar mass (Sanders et al. 2016). Electron density is most commonly probed with the \([\text{S}\,\text{n}]\lambda 4671/4673\) doublet ratio. MOSDEF galaxies at \(z \sim 2.3\) were found by Sanders et al. (2016) to have a median \([\text{S}\,\text{n}]\lambda 4671/4673\) doublet ratio of 1.13, corresponding densities of around \(290 \, \text{cm}^{-3}\) in the \(S^\ast\) zone of emitting nebulae, much higher than typical SDSS values \((\sim0.1 \, \text{cm}^{-3})\). We measure a global \([\text{S}\,\text{n}]\lambda 4671/4673\) ratio of 1.29 for SAMI609396B, corresponding to a density of \(118 \, \text{cm}^{-3}\). Placing SAMI609396B between the low- and high-redshift sample medians. Given the scatter about these median values in both the MOSDEF and SDSS samples (Figures 4 & 5 in Sanders et al. 2016), it is difficult to draw conclusions about how SAMI609396B compares to the two populations based on density. Using the \(O_\alpha\)\(^3\) strong-line ratio as a tracer for ionisation parameter, Sanders et al. (2016) found that, like SDSS galaxies, \(z \sim 2.3\) MOSDEF galaxies show a trend of decreasing ionisation parameter with increasing stellar mass. They find the slope of this relation to be very similar to that of SDSS galaxies, however with a \(-0.6\) dex offset toward higher \(O_\alpha\) at fixed stellar mass in the

\(^2\) https://sami-survey.org/abdr

\(^3\) \(O_\alpha\) = \([\text{O}\,\text{n}]\lambda 4959, 5007 / [\text{O}\,\text{n}]\lambda 3726, 29\) in this context
Figure 1. Left panel: g-band imaging of the SAMI609396 merger system from SDSS. Middle panel: ugi RGB composite of the system. Prominent auroral line emission is associated with SAMI609396B, the lower-left object exhibiting strong blue colour in the ugi composite. The white dashed circle in the middle panel shows the field of view observed by the SAMI IFU. The 10σ scale given for the g-band image applies also for the middle panel and corresponds to approximately 3.8 kpc in physical distance. Right panel: simulated rest-frame ugi colour composite after artificially redshifting the u-, g- and i-band imaging to z ~ 1. After redshifting, these bandpasses correspond approximately to HST filters ACS/F606W, ACS/814W, and WFC3/F160W. The pixel scale in the simulated image is 0′′.1, similar to that of HST/WFC3. The simulated depth of the image is similar to observations in 3D-HST (Yuan et al. 2020).

Figure 2. Publicly available value-added data products from SAMI DR2. Panel (a) Gas velocity from 1-component fitting. Panel (b) Gas velocity dispersion from 1-component fitting. Panel (c) Per spaxel star-formation rate (Medling et al. 2018). Panel (d) Star-forming mask. The large star-forming dominated region denoted with black ‘+’ symbols in panel (d) is characterised by very high SFR, velocity dispersions of ~30 – 80 km s⁻¹, and relative velocities of ~100 km s⁻¹ (the scale of panel a). This region, designated SAMI609396B, is spatially associated with observed auroral lines and is the target of our investigation. The black dotted circle in panel (a) indicates the point-spread function measured for this SAMI observation and applies to all panels.

To summarise, we find that the physical properties (SFR and ISM conditions) of SAMI609396B tend to be offset from median z ~ 0 values, although are generally less extreme than z ~ 2 galaxies. In combination with the high EW([O III])/Hβ, we consider that the physical properties of SAMI609396B might be analogous to intermediate-redshift (0 < z ≤ 1) galaxies. Low-mass galaxies like SAMI609396B are extremely difficult to resolve at high redshift. To visually demonstrate what a system like SAMI609396B would look like at a higher redshift, we simulate the angular size and morphology of SAMI609396 at z ~ 1 using similar techniques to those detailed in Yuan et al. (2020). The redshifted morphology is presented on the right panel of Figure 1. In order to resolve a low-mass system like SAMI609396B at z ~ 1 with comparable physical resolution of SAMI, a minimal angular resolution of 0.1″ is required. Such a fine resolution can be achieved either through ground-based adaptive optics or space instruments. The faintness of these low-mass systems also means the need for next-generation facilities such as JWST/NIRSpec and ground-based ELTs.

2.2 SAMI DR2: Value-added data products

SAMI DR2 includes a number of publicly available value-added data products, which we use to guide our initial understanding of the SAMI609396 system. Figure 2 shows publicly available maps for the gas velocity, gas velocity dispersion, and star-formation rate (Panels (a) – (c)) derived from 1-component fits. Panel (d) of Fig 2 shows a star-formation mask, determined according to Kewley et al. 2006 based on BPT & VO87 diagnostic diagrams (Baldwin et al. 1981; Veilleux & Osterbrock 1987).
with green denoting spaxels passing selection as "star-formation dominated". Figure 2 shows that much of the SAMI field-of-view is dominated by emission from non-star-forming sources (yellow spaxels; "other"). The yellow spaxels have higher velocity dispersion compared with star-forming dominated regions, characteristic of emission from shock-heated gas. The BPT diagram and the origin of emissions in these regions are discussed further in §5.2. The prominent auroral line emission we identify is spatially associated with the large star-formation dominated region in the left-hand (eastern) portion of the star-formation mask. This region has a median rest-frame gas velocity of $v_{\text{gas}} \approx 100$ km s$^{-1}$ (refer to scale in Fig 2), a velocity dispersion of range $\sigma_{\text{gas}} \approx 30 - 80$ km s$^{-1}$, and high a star-formation rate (median SFR surface density $\approx 0.97$ $M_\odot$ yr$^{-1}$ kpc$^{-2}$).

We designate this object as "SAMI609396B" and define its selection within the SAMI609396 datacube as including spaxels labelled as star-formation dominated with $v_{\text{gas}} > 0$, denoted by black ‘+’ symbols in panel (d) of Fig 2. Global SFR and stellar mass estimates for SAMI609396B and its companion galaxy are provided in Table 1. Details of how these are derived are provided in Appendix B.

### 3 SPATIALLY RESOLVED ELECTRON TEMPERATURE

The electron temperature ($T_e$) and electron density ($n_e$) are fundamental physical parameters in understanding the emission line physics of ionized nebulae. Abundance measurements from collisionally excited lines in H\textsc{ii} regions are very sensitive to these parameters. For this reason, chemical abundances derived following explicit measurements of $T_e$ and $n_e$ are generally used as a baseline calibration for understanding the chemistry of ionized nebulae (e.g. Maiolino & Mannucci 2019).

This is generally achieved with the so-called "direct method" via measurement of an auroral emission line and a strong nebular line of the same ionic species. This is most commonly applied to the O$^{3+}$ ion using the $[\text{O} \text{III}] / [\text{O} \text{II}]$ ratio, which is primarily sensitive to $T_e$ (its $n_e$ dependence is minimal over the density range of typical H\textsc{ii} regions). Within the typical rest-frame near-ultraviolet to near-infrared wavelength range observed for galaxies, auroral line ratios may be observable for a number of ionic species including O$^+$, N$^+$, S$^{2+}$ and S$^+$, each of which probe different zones within the emitting H\textsc{ii} regions according to the distribution of those ions within the nebular structure. Although we detect auroral lines from three ionic species in SAMI609396B ([S\textsc{ii}], [O\textsc{iii}] and [S\textsc{iii}]), we are able to derive electron temperature for only the [O\textsc{iii}] and [S\textsc{iii}] ionisation zones as we lack the spectral coverage to measure the [S\textsc{ii}]/[S\textsc{iii}] strong lines required to derive $T_e$ ([S\textsc{iii}]).

### 3.1 Auroral Emission Line Measurements

We derive flux maps for auroral lines from three ionic species ([S\textsc{ii}], [O\textsc{iii}], [O\textsc{ii}], and [S\textsc{iii}]) in the SAMI609396 data cube, as the SAMI DR2 value-added data products do not include emission line maps for these fainter lines. We concurrently re-derive strong emission line fluxes, rather than use SAMI DR2 emission line maps, ensuring self-consistency in our line ratio measurements. These flux maps are generated by applying standard methods to each spaxel, first fitting the stellar continuum, and then simultaneously fitting profiles to each emission line included in our analysis. Details of this spectral fitting are provided in Appendix C.

We obtain $S/N \sim 3 - 15$ in individual spaxels for each of [O\textsc{ii}], [O\textsc{iii}], [S\textsc{ii}], [O\textsc{ii}], 76 and [S\textsc{iii}] across the majority of the spatial region selected as SAMI609396B. We identify from visual inspection some degree of blending between [O\textsc{ii}], [O\textsc{iii}] and a neighbouring faint [Fe\textsc{ii}] emission line at $\lambda 4360$, similar to that observed in other recent studies (e.g. Curti et al. 2017; Berg et al. 2020; Arellano-Córdova & Rodríguez 2020). We find that the [O\textsc{ii}] and [O\textsc{iii}] lines are brighter than [O\textsc{ii}] and [O\textsc{iii}] flux. Our efforts to test the reliability of our [O\textsc{ii}] and [O\textsc{iii}] flux measurements are outlined in detail in Appendix C3.

### 3.2 [O\textsc{iii}] Electron Temperature

The emission line ratio most widely used to determine the electron temperature with the direct method is the [O\textsc{iii}]/[O\textsc{ii}].4363 / [O\textsc{ii}].5007 ratio. Despite the primary dependence of this [O\textsc{ii}] ratio on temperature, the residual density dependence is often accounted for by measurement of a density sensitive line ratio, typically [S\textsc{iii}].6716 / [S\textsc{ii}].6731. Izotov et al. (2006) use relations derived for these aforementioned [O\textsc{ii}] and [S\textsc{ii}] line ratios (Equations (1) and (2) in that reference) in an iterative manner, solving simultaneously for $T_e$ and $n_e$. This iterative approach is shared by the getCrossTemDen routine in the PyNeb package (Luridiana et al. 2015), which allows for a flexible array of temperature- and density-sensitive line ratios.

However, it is important to consider that neither temperature nor density is expected to be constant throughout H\textsc{ii} regions. Additionally, emission from different ionic species may not be co-spatial. Certainly, [S\textsc{ii}] emission is expected to arise from the outer regions of nebulae, thus densities measured from the [S\textsc{ii}] line ratio do not necessarily provide a good indication of the density of the [O\textsc{ii}] emission region (see Figure 2 in Kewley et al. 2019).

Given these uncertainties, Nicholls et al. (2020) instead propose a simplified approach in which $T_e$ is derived from an empirical relation of the auroral line ratio, derived from H\textsc{ii} region modelling, forgoing any attempt to account for $n_e$, suggesting that any improvements in temperature insight are outweighed by uncertainties induced by density variations and lack of co-spatiality.

Given the ~1 kpc spatial resolution of SAMI, we are unable to resolve individual H\textsc{ii} regions, adding to the uncertainties described above. Thus, we use this simplified approach to derive our $T_e$ from

| Table 1. Global properties of SAMI609396B and its companion. |
|---------------------------------------------------------------|
| **Right Ascension** | $11^h42^m12.25^s$ |
| **Declination** | $+00^\circ20'04''$ |
| **z** | 0.01824 |
| **SAMI609396B:** |
| **SFR ($M_\odot$ yr$^{-1}$)** | $4.21 \pm 0.30$ |
| **log($M_\odot/M_\odot$)** | $9.18 \pm 0.05$ |
| **Companion:** |
| **SFR ($M_\odot$ yr$^{-1}$)** | $0.32 \pm 0.08$ |
| **log($M_\odot/M_\odot$)** | $9.88 \pm 0.07$ |

*SFR measurement for area within SAMI FoV (see Fig 1). This is best considered as a lower bound.*
the [O III] / [O II] λ5007 ratio according to the relation given in Nicholls et al. (2020). This relation is shown as Equation 1 here:

$$\log_{10}(T_e([\text{OIII}])) = \frac{3.3027 + 9.1917x}{1.0 + 2.092x - 0.1503x^2 - 0.0093x^3}$$  \hspace{1cm} (1)$$

where \(x = \log_{10}(f_{\text{OIII}}/f_{\text{SII}})\), with \(f_X\) referring to a line flux measurement of a collisionally excited line with rest-frame wavelength \(X\) Å, and \(T_e\) is in units of K. The derived [O III] temperature map for spaxels with [O III] λ5003 of S/N > 3 is shown in Figure 3.

3.3 [SII] Electron Temperature

In addition to \(T_e([\text{OII}])\), spatially resolved measurements of the [S II] auroral lines allow us to measure \(T_e([\text{SII}])\) from the [S II] λ4069, 76 / [S II] λ6716, 31 ratio.

Modelling indicates that at the low density limit (\(1 < n_e < 50\) cm\(^{-3}\)), the residual density dependence of the [S II] λ4069, 76 / [S II] λ6716, 31 ratio is minimal. In contrast to the [O III] case, this [S II] temperature diagnostic is co-spatial with the [S II] density diagnostic, meaning that we are able to make a more reliable estimate of the density. The \(n_e\) values for SAMI609396 obtained with the [S II] λ6716 / [S II] λ6731 ratio (Eq. 3 in Proxauf et al. 2014) are shown in Fig 4 Panel (b). We find the median electron density to be \(n_e = 92\) cm\(^{-3}\). This value is above the [S II] low density limit, indicating that [S II] λ4069, 76 / [S II] λ6716, 31 will have a residual density dependence. Nonetheless, we derive the [S II] temperature with a similar approach to that outlined in §3.2 with a new rational polynomial fit to modelling data assuming a density of \(n_e = 100\) cm\(^{-3}\). This fit is given in Equation 2 where \(x = \log_{10}(f_{\text{OIII}} + f_{\text{SII}})/(f_{\text{OIII}} + f_{\text{SII}})\) and \(T_e\) is in units of K.

$$\log_{10}(T_e([\text{SII}])) = \frac{-0.08891 + 2.06354x + 3.38680x^2 + 0.10754x^3}{0.1 + 0.78000x + 0.94404x^2}$$  \hspace{1cm} (2)$$

\(T_e([\text{SII}])\) values obtained for SAMI609396 are compared with \(T_e([\text{OII}])\) values in Figure 4. Panels (a) and (b) show maps of \(T_e([\text{SII}])\) and \(T_e([\text{OII}])\) respectively for spaxels where the relevant auroral line is detected with S/N > 5. Panel (e) shows the direct comparison of \(T_e([\text{SII}])\) and \(T_e([\text{OII}])\) values on a spaxel-by-spaxel basis. We observe that a majority of points in panel (e) of Fig 4 lie below the line of \(T_e([\text{SII}]) = T_e([\text{OII}])\) (i.e. higher \(T_e([\text{OII}])\) than \(T_e([\text{SII}])\)). The large blue and red points in Fig 4 Panel (e) show derived \(T_e([\text{SII}])\) and \(T_e([\text{OII}])\) electron temperatures for two mock apertures which correspond to the regions shown as blue and red dashed circles in Panel (a). These aperture temperatures appear to indicate that \(T_e([\text{SII}])\) and \(T_e([\text{OII}])\) do not exhibit strong positive correlation across different spatial regions of SAMI609396B. The implications of this temperature relation for metallicity measurement are discussed further in §4.

4 SPATIAL TRENDS IN METALLICITY

In Section 3 we derived spatially resolved electron temperature \(T_e\) measurements. Here we use these \(T_e\) measurements to determine direct method oxygen abundances under three different sets of assumptions, showing that derived spatial variations in metallicity can be very sensitive to the assumed initial H II region temperature structure. Additionally we derive spatially resolved strong-line metallicities and discuss differences in observed spatial trends.

4.1 Direct Method Metallicity

Since the abundance of neutral oxygen \((O^0)\) and oxygen in ionization states higher than \(O^2+\) is expected to be negligible in H II regions, we assume that the total oxygen abundance can be approximated as Equation 3:

$$\frac{O}{H} = \frac{O^+}{H^+} + \frac{O^{2+}}{H^+}.$$  \hspace{1cm} (3)$$

We derive abundances of these two ionisation states of oxygen using the following analytic relations set out in Pérez-Montero (2017):
Resolved direct metallicity in SAMI

Figure 4. Comparison of $T_e([\text{O}iii])$ and $T_e([\text{S}ii])$ electron temperature values. Panel (a): map of $T_e([\text{O}iii])$ values for spaxels with $S/N > 5$ for [O iii] $\lambda$4363. Red circle labelled ‘PSF’ has diameter equal to the FWHM of the SAMI PSF for this observation and applies to panels (a–d). Panel (b): electron density derived from the [S ii] $\lambda\lambda$6716 / $\lambda$6731 ratio. Panel (c): map of $T_e([\text{S}ii])$ values for spaxels with $S/N > 5$ for [S ii] $\lambda\lambda$4069, 76. Panel (d): map of $T_e([\text{S}ii])$ from panel (c) smoothed with a Gaussian filter. Panel (e): Brown points show values of of $T_e([\text{S}ii])$ and $T_e([\text{O}iii])$ for individual spaxels with $S/N > 5$ on both auroral lines. Error bars shown reflect only measurement uncertainty and do not include associated modelling uncertainties. Temperatures derived for two mock apertures (indicated by blue and red dashed circles in panel a) are shown as the blue and red points in panel (e).

12 + log \left( \frac{O^{2+}}{H^+} \right) = \log \left( \frac{f_{\lambda 4959} + f_{\lambda 5007}}{f_{H\beta}} \right) + 6.1868
+ 1.2491 \left( \frac{t(O^{2+})}{t(H^+)} \right) - 0.5816 \cdot \log \left( \frac{t(O^{2+})}{t(H^+)} \right)
\quad \text{(4)}

12 + log \left( \frac{O^+}{H^+} \right) = \log \left( \frac{f_{\lambda 3726} + f_{\lambda 3729}}{f_{H\beta}} \right) + 5.887 + 1.641 \left( \frac{t(O^+)}{t(H^+)} \right)
- 0.543 \cdot \log \left( \frac{t(O^+)}{t(H^+)} \right) + 0.000114 \cdot n_e
\quad \text{(5)}

where $t(O^{2+}) = T_e([\text{O}iii])/10^4$ K, $t(O^+)$ = $T_e([\text{O}ii])/10^4$ K, $n_e$ is the electron density measured by the [S ii] $\lambda\lambda$6716 / $\lambda$6731 ratio, and $f_X$ refers to a line flux measurement of the $H\beta$ Balmer line or a collisionally excited line with rest-frame wavelength $X$. Deriving $O^{2+}/H^+$ in this way requires only [O iii] $\lambda\lambda$4959, 5007 and $H\beta$ emission line fluxes in addition to the $T_e([\text{O}iii])$ values derived in § 3.2. On the other hand, the $O^+/H^+$ abundance from Eq. 5 calls for $T_e([\text{O}ii])$, which we do not directly measure. Additionally, $O^+/H^+$ has residual dependence on $n_e$, although we simply adopt the same fixed density $n_e = 100$ cm$^{-3}$ used in the temperature calculations in §3.2. Note that our derived metallicity values vary by less than 0.01 dex with changes in adopted density, provided those are below $n_e < 200$ cm$^{-3}$.

Unlike $T_e([\text{O}iii])$, we do not directly measure $T_e([\text{O}ii])$, since we are unable to detect either the [O iii] $\lambda\lambda$4939, 5007 or [O ii] $\lambda\lambda$3726, 3729 doublet. A viable alternative is to use temperatures derived from other ion species, especially [N ii] or [S ii], to probe the temperature structure (e.g. Berg et al. 2020). However, given the faintness of auroral lines it is common that an observation may enable measurement of only the [O iii] temperature zone. In this scenario, a $T_e([\text{O}ii])$ estimate can be obtained by adopting an empirical $T_e([\text{O}iii])$ – $T_e([\text{O}ii])$ relation, for which a number of calibrations exist (e.g. Izotov et al. 2006; López-Sánchez et al. 2012). Despite expanding the number of observations for which direct metallicities can be derived, Yates et al. (2020) (Y20 hereafter) find that using $T_e([\text{O}iii])$ – $T_e([\text{O}ii])$ relations can underestimate the direct metallicity by more than 0.5 dex for low-ionisation systems, highlighting the importance of constraining the internal temperature structure of H ii regions where possible. Additionally, Y20 provide an empirical correction for this effect based on the [O iii] / [O ii] strong line ratio.

For this analysis, we determine our total oxygen abundance maps in three ways. Each differs in its approach to handling the $O^+/H^+$ abundance, while in all three cases the $O^{2+}/H^+$ abundance is determined from Eq 4 and our direct measurement of $T_e([\text{O}ii])$. For the remainder of this paper, metallicities derived in these three ways will be abbreviated as $Z_{\text{Te;LS12}}$, $Z_{\text{Te;Y20}}$ and $Z_{\text{Te;SII}}$ (where $Z = 12 + \log(O/H)$), described as follows:

(i) $Z_{\text{Te;LS12}}$: $O^+/H^+$ is determined using $T_e([\text{O}ii])$ derived from $T_e([\text{O}iii])$ using the relation outlined in López-Sánchez et al. (2012) (Eq 6). This is the most commonly adopted method.

(ii) $Z_{\text{Te;Y20}}$: As for $Z_{\text{Te;LS12}}$, with the subsequent application of the Y20 empirical correction, based on [O iii] / [O ii] strong-line ratio (Eq 7). This is a relatively new correction and has not been widely implemented in literature yet.

(iii) $Z_{\text{Te;SII}}$: $O^+/H^+$ is determined with $T_e([\text{O}ii])$ derived instead from $T_e([\text{S}ii])$ using the assumption $T_e([\text{O}ii]) = T_e([\text{S}ii])$. This is uniquely enabled by the detection of [S ii] auroral lines in this study.

4 We note that alternative $T_e([\text{OII}])$ – $T_e([\text{OIII}])$ relations, including the equations from Izotov et al. (2006), do not significantly affect the metallicity morphology obtained for SAMI609396B.
Figure 5. Observed spatial trends in direct method metallicity depend strongly on temperature structure assumptions. Direct method metallicity maps (panels a–c) and spatial metallicity trends (d–f) are shown for SAMI609396B under three different \( \Delta T_e (O\,\text{III}) \) temperature assumptions. Panels (a, d) show \( Z_{\text{Te;LS12}} \) where \( T_e (O\,\text{III}) \) is derived from \( T_e (O\,\text{II}) \) via the relation of Lopez-Sanchez et al. (2012) (Eq 6). Panels (b, e) show \( Z_{\text{Te;Y20}} \) derived as for \( Z_{\text{Te;LS12}} \) with the additional step of applying the empirical correction of Y20 based on O32. Panels (c, f) show \( Z_{\text{Te;SII}} \) : metallicity is derived assuming \( T_e (O\,\text{II}) = T_e (S\,\text{II}) \). See §4.1 for details. Maps in panels (a–b) include spaxels with measurement uncertainty contribution from the high certainty of the \( [O\,\text{III}] \) derived in Fig 3 and favours a strong trend in metallicity across the region of highest S/N over the coming sections.

| Panel | Description |
|-------|-------------|
| (a)   | \( Z_{\text{Te;LS12}} \) |
| (b)   | \( Z_{\text{Te;Y20}} \) |
| (c)   | \( Z_{\text{Te;SII}} \) |
| (d)   | Spatial trend for \( [O\,\text{III}] \) emission |
| (e)   | Spatial trend for \( [O\,\text{II}] \) emission |
| (f)   |Spatial trend for \( S\,\text{II} \) emission |

4.1.1 Empirical \( T_e (O\,\text{III}) \)–\( T_e (O\,\text{III}) \) relation

For \( Z_{\text{Te;LS12}} \) we adopt the \( T_e (O\,\text{III}) \)–\( T_e (O\,\text{III}) \) relation as calibrated by Lopez-Sanchez et al. (2012), given in Equation 6:

\[
T_e (O\,\text{III}) = T_e (O\,\text{III}) + 450 - 70 \cdot \exp \left( \frac{T_e (O\,\text{III})}{5000} \right)^{1.22} \tag{6}
\]

Deriving \( T_e (O\,\text{III}) \) in this way and applying Equations 4–5 we obtain the total oxygen abundance map shown in panel (a) of Fig 5. The spatial structure of this map reflects that of the temperature map derived in Fig 3 and favours a strong trend in metallicity across the region of the highest signal-to-noise (Fig 5, panel d).

The measurement uncertainty is dominated by the flux uncertainty of the \( [O\,\text{III}] \)4363 emission line to the point where the measurement uncertainty contribution from the high \( S/N \) \( [O\,\text{III}] \), \( [O\,\text{II}] \) and H\( \beta \) strong lines can be ignored. We see no obvious correlation between the \( S/N \) of \( [O\,\text{III}] \)4363 and \( T_e (O\,\text{III}) \) (Fig 3). Increasing the minimum \( S/N \) cut on the \( [O\,\text{III}] \)4363 auroral line from \( S/N > 3 \) to \( S/N > 8 \) changes the median metallicity by less than 0.005 dex. Together, these give us confidence that observed spatial variations in metallicity are not artifacts from measurement noise, although the effects of modelling uncertainty are discussed over the coming sections.

4.1.2 Empirical \( O^+ \) Abundance Correction

Yates et al. (2020) provide an empirical correction based on the observed \( [O\,\text{III}] / [O\,\text{II}] \) line ratio given by Equation 7.

\[
Z_{\text{Te;Y20}} = Z_{\text{Te;LS12}} - 0.71 \cdot (O32 - 0.29) \tag{7}
\]

where \( Z_{\text{Te;Y20}} \) and \( Z_{\text{Te;LS12}} \) are corrected and uncorrected values of \( 12+\log(O/H) \) respectively; \( O32 = \log([O\,\text{III}] \lambda 4959,5007 / [O\,\text{II}] \lambda 3726, 9) \) and the correction is applied only when \( O32 \leq 0.29 \).

Values of \( O32 \) across SAMI609396B fall in the range for which this correction will be non-zero. Our direct metallicity map after Y20 correction is shown in Fig 5 Panel (b). Spatial variations in the \( O32 \) ratio result in a flattening of the spatial trend after application of this correction.

We note that, in addition to the empirical correction described here (“Y20 correction”), Yates et al. (2020) also outlined a novel method for determining semi-direct metallicities (“Y20 method”) in which \( T_e (O\,\text{III}) \) and metallicity are solved for simultaneously, rather than sequentially. This Y20 method then also requires subsequent application of the Y20 correction if \( O32 \leq 0.29 \), as above. Note that Figure 6 in Yates et al. (2020) shows that the abundance deficit at low \( O^+ / O^+ \), which the Y20 correction adjusts for, is present to
varying degrees for all $T_e([O\,{\text{ii}}]) \sim T_e([N\,{\text{ii}}])$ relations considered in that work.

We find the Y20 method gives a two-valued solution for SAMI609396B which may require an additional prior to select the best metallicity solution. We found that applying the Y20 method as originally outlined favoured the lower value of these two solutions which yielded a gradient comparable to that obtained from our $Z_{\text{Te}}, Y20$ approach here, albeit with a much lower normalisation (~0.3 dex). We found that the normalisation of the upper-branch solution was in better agreement with our other determinations outlined here, however the spatial trend arising from this upper-branch solution is more difficult to interpret. Discussion of our implementation of the Yates et al. (2020) method and its two-valued nature is deferred to Appendix D.

4.1.3 $O^+$ abundance with $T_e([S\,{\text{ii}}])$

The $[S\,{\text{ii}}]$ temperature samples a relatively narrow zone from the outer regions of nebulae and is consequently not widely used to constrain the temperature profile of emitting $H\,\alpha$ regions. However, Croxall et al. (2016) found general agreement of $T_e([S\,{\text{ii}}])$ with $T_e([O\,{\text{ii}}])$ and $T_e([N\,{\text{ii}}])$ in $H\,\alpha$ regions in NGC 5457. In the absence of the $[S\,{\text{ii}}]$ strong-lines, the $[N\,{\text{ii}}]$ auroral lines, or any other temperature probes, $T_e([S\,{\text{ii}}])$ affords our only direct probe of the internal temperature structure of $H\,\alpha$ regions in SAMI609396B.

We make the simplified assumption that $T_e([O\,{\text{ii}}]) = T_e([S\,{\text{ii}}])$ and update our total oxygen abundance using the measured $T_e([S\,{\text{ii}}])$ map (Fig 4 panel c) to re-derive our $O^+/H^+$ values. These updated oxygen abundances are shown in Fig 5 Panel (c), spanning a slightly smaller spatial extent due to the additional requirement of $[S\,{\text{ii}}]$ auroral line signal-to-noise. The spatial trend shown in Fig 5 Panel (f) is seen to be opposite of that in Panel (d) where $O^+/H^+$ was derived using an empirical temperature relation, albeit with a larger scatter.

This stark reversal can be explained by the $T_e([S\,{\text{ii}}]) \sim T_e([O\,{\text{ii}}])$ trends observed in Figure 4. Deriving $T_e([O\,{\text{ii}}])$ from a relation with $T_e([O\,{\text{ii}}])$ assumes that such a relation is fixed across the spatial region covered. This would mean that regions with elevated $T_e([O\,{\text{ii}}])$ would also show increased $T_e([S\,{\text{ii}}])$. However, the aperture plots in panel (e) of Fig 4 (blue and red bold points) show that despite the increase in $T_e([O\,{\text{ii}}])$ from the ‘blue’ aperture to the ‘red’ aperture, measured $T_e([S\,{\text{ii}}])$ instead decreases (albeit with large uncertainties). This suggests the absence of a strong positive correlation between these temperatures across the spatial region and highlights the limitations of applying empirical temperature relations to measure spatial metallicity trends. This is likely driven by variations in the ionisation structure (i.e. $O^+/O^+$ abundance ratio) and also explains the observed variations in $O32$ ratio that lead to the flattening of the spatial trend observed after applying the Y20 correction. We discuss this further in § 4.3.

4.2 Strong-Line Metallicity

In Figure 6 we compare four different strong-line metallicity maps with $Z_{\text{Te}}, LS12$ and $Z_{\text{Te}}, Y20$ direct method metallicity maps derived in §4.1. Strong-line metallicities are derived using a selection of widely strong-line diagnostics, defined in Equations 8 – 13:

$$N2O2 = \log_{10} \left(\frac{[N\,{\text{ii}}]/[O\,{\text{ii}}]}{[O\,{\text{ii}}]/[O\,{\text{ii}}]}\right)$$  \hspace{1cm} (8)

$$O32 = \log_{10} \left(\frac{[O\,{\text{iii}}]/[O\,{\text{ii}}]}{[O\,{\text{ii}}]/[O\,{\text{ii}}]}\right)$$  \hspace{1cm} (9)

$$R_{23} = \log_{10} \left(\frac{[O\,{\text{ii}}]/4959 + [O\,{\text{iii}}]/5007 + [O\,{\text{ii}}]}{H\beta}\right)$$  \hspace{1cm} (10)

$$N2 = \log_{10} \left([N\,{\text{ii}}]/H\alpha\right)$$  \hspace{1cm} (11)

$$O3/2N2 = \log_{10} \left(\frac{[O\,{\text{iii}}]/H\beta - N2}{N2}\right)$$  \hspace{1cm} (12)

$$N2S2H\alpha = \log_{10} \left(\frac{[N\,{\text{ii}}]/[S\,{\text{ii}}]}{0.264 \cdot N2}\right)$$  \hspace{1cm} (13)

where $[N\,{\text{ii}}] = ([N\,{\text{ii}}]_6583, [O\,{\text{ii}}]_3726 + [O\,{\text{ii}}]_3729), [S\,{\text{ii}}] = ([S\,{\text{ii}}]_6716 + [S\,{\text{ii}}]_6731),$ and $[O\,{\text{ii}}]_5007$ unless otherwise specified. We use strong-line calibrations based on a mixture of theoretical and observational calibrations, outlined as follows:

- **N2O2:** We use the theoretical calibration provided in Kewley et al. (2019) to solve iteratively for metallicity and ionisation parameter using the $N2O2$ (Eq. 8) and $O32$ (Eq. 9) diagnostic line ratios.

- **$R_{23}:$$** We use the calibration provided by Curti et al. (2020a) based on direct method measurements of stacked SDSS galaxies. The $R_{23}$ ratio (Eq. 10) is two-valued with a turnover at around $12+\log(O/H) = 8.1$. Using $N2$ (Eq. 11) to distinguish between high- and low-metallicity branches, we find $N2 > 1.0$ across the extent of SAMI609396B, prompting us to consider only the high-metallicity branch.

- **O3N2:** Calibration based on large compilation of $T_e$ measurements in $H\,\alpha$ regions from Marino et al. (2013).

- **N2S2H\alpha:** This diagnostic was proposed by Dopita et al. (2016) based on predictions from photoionisation modelling. We adopt the calibration presented therein.

The colour maps shown in Fig 6 are shown with different normalisation so as to visualise any spatial trends in metallicity in each diagnostic, setting aside the expected discrepancies in normalisation between alternative diagnostics (e.g. Kewley & Ellison 2008). Indeed, even after applying the Y20 correction, the median direct method metallicity ($Z_{\text{Te}}, Y20 = 8.40$) is still nearly 0.3 dex lower than that of the theoretically calibrated $N2O2$ diagnostic ($Z_{\text{Te}}, N2O2 = 8.68$). This difference is consistent with previous work which has shown systematic offset between metallicities derived from $N2O2$ using theoretical and empirical calibrations (Bresolin et al. 2009; Bresolin & Kennicutt 2015).

4.3 Is The Metallicity Gradient Positive Or Negative?

While it is widely known that different metallicity measurement techniques often disagree in normalisation, one would hope that at a minimum two methods should agree on the ranked order of metallicities they measure. It is immediately striking from Fig 6 that even qualitative spatial trends in metallicity are very sensitive to the adopted diagnostic. Figure 7 illustrates these spatial trends as a 1D projection. Given the distorted morphology of SAMI609396B, we do not formally define a metallicity gradient, but instead examine 1D spatial trends along the mock slit shown in Fig 5 panels (a-c) and Fig 6 panel (f). This slit encompasses the region of highest emission line signal-to-noise and approximately corresponds to the region of highest $g$-band flux (Fig 1).

Panel (a) of Fig 7 shows the running medians in metallicity with projected distance along this mock slit for all four strong-line
Figure 6. Direct method and strong-line oxygen abundance maps for the star-formation selected region corresponding to SAMI609396B. Panel (a): Direct method metallicity using $T_e$ values derived from [O iii] $\lambda 4363 / \lambda 5007$ ratio (see §4.1). Panel (b): Direct method metallicity after applying the empirical correction of Yates et al. (2020) (see §4.1.2). Panel (c): iterative solution for metallicity, solved simultaneously for metallicity with $N2O2$ and ionisation parameter with $O3$ using calibrations from Kewley et al. (2019). Panel (d): metallicity from $R_{23}$ strong-line diagnostic using calibration from Curti et al. (2020a). Panel (e): metallicity derived from $O3N2$ using calibration from Marino et al. (2013). Panel (f): metallicity derived from the $N2S2H\alpha$ diagnostic as outlined in Dopita et al. (2016). The peak $i$-band flux from SDSS imaging is marked in each panel with a white pentagon. FWHM of the spatial PSF is shown by the red circle in panel (f). The slit shown in panel (f) spans the region of highest S/N for the [O iii] $\lambda 4363$ line and is examined in detail in Fig 7.

Figure 7. Spatial trend in metallicity along a mock slit for seven different strong-line and direct method metallicity measurement techniques. Panel (c) shows individual spaxels and running median trends measured with $N2O2$ (red), $O3N2$ (black), $R_{23}$ (blue) and $N2S2H\alpha$ (magenta). Colour coding is as indicated in the legend in panel (a). More details on these strong-line metallicities can be found in § 4.2. Panel (b) reproduces trend lines for three different direct method assumptions from Fig 5 for ease of comparison. Panel (a) renormalises each of these seven trend lines to show metallicity deviation. The horizontal axis is zeroed at the adopted core of SAMI609396B, taken as the location of the peak in $i$-band flux from SDSS imaging. Vertical error bars show the measurement uncertainty carrying through from emission line measurements. Horizontal error bars indicate the FWHM of the spatial PSF of the SAMI observation in terms of physical distance.
methods described in § 4.2 as well as the three different direct method assumptions outlined in § 4.1. The distance axis has been zeroed at the location of peak i-band flux from SDSS imaging which we adopt as the core of SAMI609396B. Each trend line has been renormalised relative to the metallicity at \( r = -1.3 \) kpc. We renormalise at this projected distance rather than the core as the three direct method approaches show best agreement in this spatial region (Fig 7 Panel b). In particular, the Y20 empirical corrections are smallest in this region.

Most striking in Fig 7 Panel (a) is the clear discrepancy between the \( Z_{\text{TE; LS12}} \) direct method and all other methods. The \( Z_{\text{TE; LS12}} \) method favours a strong trend of decreasing metallicity left-to-right from negative projected distance toward the core. Strong-line methods show an opposite trend, with metallicity increasing in the same direction albeit with less overall deviation from uniform. As outlined in § 4.1, we find that the \( Z_{\text{TE; Y20}} \) and \( Z_{\text{TE; SII}} \) direct methods both show a much flatter metallicity trend than the \( Z_{\text{TE; LS12}} \) method, and are in better agreement with strong-line methods.

Given that strong-line methods have their own unsettled systematic uncertainties (Section 5.1), we do not assess the absolute correctness of ‘gradients’ derived from each method. Instead, we discuss below the physical reason for why the gradient from the \( Z_{\text{TE; LS12}} \) method is at odds with \( Z_{\text{TE; Y20}} \) and \( Z_{\text{TE; SII}} \) and the strong line methods.

### 4.4 O\textsuperscript{2+}/O\textsuperscript{+} abundance ratio variation

We attribute the cause of the discrepancy between \( Z_{\text{TE; LS12}} \) and other methods to variations in the \( O\textsuperscript{2+}/O\textsuperscript{+} \) abundance ratio, causing deviations from the fixed \( T_e([O\text{II}]) − T_e([O\text{III}]) \) relation adopted by \( Z_{\text{TE; LS12}} \). Figure 8 shows separate \( O\textsuperscript{+}/H\textsuperscript{+} \) and \( O\textsuperscript{2+}/H\textsuperscript{+} \) abundance maps, derived using \( T_e([S\text{II}]) \) and \( T_e([O\text{III}]) \) respectively, with panel (a) showing elevated \( O\textsuperscript{+}/H\textsuperscript{+} \) in the core region (lower-right; corresponding to Projected Distance \( \approx 0 \) kpc in horizontal scale of Fig 7).

A bulk change in the ionisation structure of H II regions across SAMI609396B such as would cause measured temperatures to deviate from the \( T_e([O\text{II}]) − T_e([O\text{III}]) \) relation from López-Sánchez et al. (2012) (Eq 6).\(^5\) In § 3.3 we noted that \( T_e([S\text{II}]) \) and \( T_e([O\text{III}]) \) derived for two mock apertures indicated the absence of a strong positive correlation between \( T_e([S\text{II}]) \) and \( T_e([O\text{III}]) \) (Fig 4 Panel e). In particular, lower \( T_e([S\text{II}]) \) values obtained in the core region leads to systematically higher \( O\textsuperscript{+} \) abundance measurements in \( Z_{\text{TE; SII}} \) than \( Z_{\text{TE; LS12}} \), driving the apparent reversal in the measured total oxygen abundance gradient.

Recently, Yates et al. (2020) observed that for \( \log(O\textsuperscript{2+}/O\textsuperscript{+}) \leq 0.0 \), “semi-direct” metallicities (that is, metallicities in which \( T_e([O\text{II}]) \) has been directly measured, but \( T_e([O\text{III}]) \) has been indirectly determined using an assumed \( T_e([O\text{II}]) − T_e([O\text{III}]) \) relation) underestimated the total metallicity by up to \( \sim 0.5 \) dex compared with metallicities derived using direct measurements of both \( T_e([O\text{II}]) \) and \( T_e([O\text{III}]) \). This effect also correlates with the \( [O\text{II}]/[O\text{III}] \) strong-line ratio, motivating the Y20 correction for observations with \( \log([O\text{II}]/[O\text{III}]) \leq 0.29 \).

Figure 8 shows that \( O\textsuperscript{2+}/O\textsuperscript{+} \) abundance ratios in SAMI609396B largely fall below \( \log(O\textsuperscript{2+}/O\textsuperscript{+}) \leq 0.0 \), inside the range highlighted in Y20 as giving rise to deficits in the total oxygen abundance when “semi-direct” methods are used. Furthermore, a spatial trend in \( O\textsuperscript{2+}/O\textsuperscript{+} \) abundance ratio can be seen in panel (c) of Figure 8, with lower \( O\textsuperscript{2+}/O\textsuperscript{+} \) in the lower-right regions of SAMI609396B. Y20 found that the “semi-direct” abundance deficit is more pronounced at lower values of \( O\textsuperscript{2+}/O\textsuperscript{+} \). From this, we reason that it is likely that \( Z_{\text{TE; LS12}} \) underestimates the total oxygen abundance across the majority of SAMI609396B. In particular, the lower \( O\textsuperscript{2+}/O\textsuperscript{+} \) seen in the core of SAMI609396B indicate that the systematically lower metallicities obtained in the core versus higher radius for \( Z_{\text{TE; LS12}} \) (panel d of Figure 5) can be explained by this semi-direct abundance deficit being amplified in the core region.

By not appropriately accounting for this trend, when applying the \( Z_{\text{TE; LS12}} \) method the \( O\textsuperscript{2+}/O\textsuperscript{+} \) abundance ratio trend instead masquerades as the trend in total oxygen abundance seen in Fig 5 & 7.

### 5 DISCUSSION

#### 5.1 Finer metallicity trends from strong lines

The measurement uncertainties on direct method metallicities for SAMI609396B are too large to be used for anything more than the bulk trend. While the strong-line methods show general agreement when considered in this bulk fashion, deviations exist in the finer details of their spatial trends (Fig 6 panels c-f & Fig 7 panel c). Most notable is the tendency of O3N2 to continue to increase be-

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\(^5\) Or, indeed, any fixed monotonic relation assumed between \( T_e([O\text{II}]) \) and \( T_e([O\text{III}]) \).
yon the core ($r > 0$ kpc in Fig 7), out to the boundary of the star-formation selected region. While other strong line methods, especially $N2S2\beta$ and $N2O2$, favour a peak in metallicity around $r = -0.6$ kpc and decreasing past the core and beyond. We explore the possibility of this tension as arising from contaminating emission from non-star-forming sources below in § 5.2.

5.2 Dissecting the Emission Line Excitation Mechanisms on the BPT Diagram

Gas-phase metallicity studies such as this aim to determine abundances of nebulae photoionised by recently formed O- and B-type stars ($H\alpha$ regions). However, emission from other sources including active galactic nuclei (AGN), shock-heated gas (shocks), and diffuse ionised gas (DIG), may contribute significantly to an observed extragalactic emission spectrum. Since each of these sources exhibit characteristically different emission spectra, inference of the properties of ionised gas from an emission line spectrum requires knowledge (or an assumption) of the excitation mechanism causing the emission.

Different excitation sources are generally distinguished with BPT or VO87 diagnostic diagrams which compare $[O\,\text{iii}]/H\beta$ to each of $[N\,\text{ii}]/H\alpha$, $[S\,\text{ii}]/H\alpha$, and $[O\,\text{i}]/H\alpha$ (Baldwin et al. 1981; Veilleux & Osterbrock 1987). Demarcation lines that separate $H\alpha$ regions from other sources of emission have been derived from photoionisation modelling (Kewley et al. 2001) and from large samples of observational data (Kauffmann et al. 2003). These can be used to exclude observations which are dominated by emission sources other than $H\alpha$ regions.

Of course, the presence of one emission source in an observation does not preclude the presence of any others. Indeed a so-called “mixing sequence” is often observed on diagnostic diagrams, spanning the regions between the loci inhabited by $H\alpha$ regions and those of other ionizing sources. Global spectra residing along this sequence are best explained as galaxies for which the global spectrum contains emission from both $H\alpha$ regions and other AGN or shocks, with the position along this mixing sequence determined by the relative proportion of each of these sources of emission. Further, when observations are made with IFU spectroscopy, mixing sequences can be spatially resolved within individual galaxies (Ho et al. 2014; Davies et al. 2014a,b, 2016, 2017; Jones et al. 2017; Zhang et al. 2017; D’Agostino et al. 2018) due to differing spatial distributions of emission sources within these galaxies.

Figure 9 shows diagnostic line ratios for individual spaxels from SAMI DR2 single component emission line fits over the full extent of the SAMI609396 merger system. Purple points are those which pass the $H\alpha$ region Kewley et al. (2001) selection criteria in all three panels. The spatial region selected as SAMI609396B analysed in this paper is a subset of these purple points (refer to Fig 2 for SAMI609396B spatial selection).

Overplotted on Fig 9 are basis points predicted from photoionisation modelling for $H\alpha$ regions (Dopita et al. 2013; green circles), fast shocks (Allen et al. 2008; blue triangle) and slow shocks (Sutherland & Dopita 2017; Dopita & Sutherland 2017; yellow inverted triangle) according to the model parameters given in Table 2. The DIG basis point (red stars) is adopted as the peak region of strong-line ratios from the 10% lowest surface brightness spaxels in the Zhang et al. (2017) MaNGA sample (Sanders et al. 2017). Black dashed lines indicate fractional mixing sequences between these basis points.

| $H\alpha$ region | $Z/Z_\odot$ | $\log(q)$ | $\kappa$ |
|-----------------|-------------|-----------|---------|
| Fast shock      | 250         | 1.0       | 10      |
| Slow shock      | 160         | 1.0       | 1000    |

$^a$Dopita et al. (2013); $^b$Allen et al. (2008)
$^c$Sutherland & Dopita (2017)
$^d$Shock basis points include 50% contribution from pre-cursor
5.2.1 Effect of contaminating emission

Given the limited (~kpc) spatial resolution of SAMI, some amount of contamination from non-star-forming emission sources is inevitable, despite limiting our analysis to the region of nominally star-forming dominated emission. Sanders et al. (2017) showed that contamination from DIG can lead to discrepancies in measured metallicity of up to ~0.3 dex. In resolved studies, Poetrodjojo et al. (2019) found that the inclusion of DIG in metallicity gradient measurements affects all diagnostics to varying degrees.

Of particular concern to establish the robustness of gradient studies is the presence of significant systematic variation in the relative contribution of H\(\alpha\) region and non-star-forming emission. This has the potential to affect the inference on spatial metallicity trends. Figure 9 suggests that spaxels in this star-forming selected region may form the beginning of a spatial mixing sequence, perhaps indicating existence of spatial variations in the fractional contribution of shock emission to the total emission. Given the multiple ways metallicities from different diagnostics can be affected by contaminating emission, these variations could help to explain differences in the apparent metallicity trends recovered.

Line ratios plotted in Figures 9 & 10 support our assumption that the “star-forming” selected spaxels associated with SAMI609396B are indeed dominated by emission from H\(\alpha\) regions. However, it should be considered that even in regions with emission “dominated” by H\(\alpha\) regions, some amount of non-star-forming emission will invariably be present. In particular, the mixing sequences shown as black dashed lines in Figure 9 highlight that there is room for variation in the relative contribution of different emission sources without moving outside the scope of what can be considered “dominated” by H\(\alpha\) regions. A quantitative assessment of this effect is beyond the scope of this paper, but we note that variable contributions of non-star-forming emission in IFU observations of galaxies has the potential to affect measured trends in gas-phase abundances.

In § 4 we showed that, aside from the \(Z_{TE; LS12}\) application of the direct method, our metallicity measurements favour a flattened metallicity gradient. This flat gradient is likely due to the effects of the merger, which are known to produce flattened metallicity gradients due to strong inflows of pristine galaxies from the outskirts of galaxies (e.g., Kewley et al. 2010). The measured gradient may be affected by the presence of shocks, however given that these metallicities were derived using a relatively small subset of the mixing sequence seen in Fig 9 (i.e. the purple points) the effect of this contribution is likely not too significant.

6 CONCLUSION

Following a search of the SAMI Galaxy Survey Data Release 2 Public Data, we identified SAMI609396B, an interacting galaxy showing high \(S/N\), spatially-resolved detections of three auroral lines: [S\(\alpha\)]\(\lambda\)4363, [S\(\alpha\)]\(\lambda\)4069, 76 and [S\(\alpha\)]\(\lambda\)6312. The source also has properties that make it a good candidate for a local analog
of high redshift galaxies, in particular for its combination of moderate stellar mass, disturbed morphology and elevated specific star formation rate (see § 2.2 & Appendix B).

We use $[O\,\text{iii}]$ and $[S\,\text{ii}]$ auroral-to-strong line ratios to derive spatially resolved electron temperature measurements for two sub-regions within the emitting $\text{H}\,\text{ii}$ regions ($T_e([O\,\text{iii}])$ and $T_e([S\,\text{ii}])$). Our results indicate the absence of a strong positive correlation between the $T_e([S\,\text{ii}])$ and $T_e([O\,\text{iii}])$ temperatures across different spatial regions in SAMI609396B. Instead, Figure 4 shows $T_e([S\,\text{ii}])$ and $T_e([O\,\text{iii}])$ appearing to trend in opposite directions between two apertures. This deviates from the common assumption of a fixed positive monotonic relation between these different temperatures.

Our $T_e([O\,\text{iii}])$ measurements allow for direct method $O^+/H^+$ abundance measurements. We then derive direct method total oxygen abundances under three different treatments of the $O^+/H^+$ abundance:

(i) $Z_{Te; LS12} = T_e([O\,\text{iii}])$ is assumed from $T_e([O\,\text{iii}]) - T_e([O\,\text{iii}])$ relation (López-Sánchez et al. 2012).

(ii) $Z_{Te; Y20}$: As for $Z_{Te; LS12}$, with additional $Y20$ empirical correction, based on $[O\,\text{iii}]/[O\,\text{iii}]$ strong-line ratio.

(iii) $Z_{Te; SII} = T_e([O\,\text{iii}])$ adopted as $T_e([O\,\text{iii}]) = T_e([S\,\text{ii}])$.

We show that the disagreement between spatial metallicity trends returned by these methods is pronounced. $Z_{Te; LS12}$ favours a strong spatial trend with much lower total oxygen abundances being measured in the core, while $Z_{Te; Y20}$ and $Z_{Te; SII}$ instead suggest a flatter spatial trend, if anything perhaps opposite to the $Z_{Te; LS12}$ trend. We conclude that the cause of this disagreement is variation in the $O^+/O^+$ abundance ratio causing deviations from the assumed $T_e([O\,\text{iii}]) - T_e([O\,\text{iii}])$ relation. Accordingly, $Z_{Te; LS12}$ results in systematically lower $O^+$ abundances across the whole of SAMI609396B than those of $Z_{Te; SII}$. This gives rise to an apparent metallicity gradient as the effect is not spatially uniform: $O^+$ abundance is particularly elevated in the core when probed by $Z_{Te; SII}$. The measured variation in the $O^+/O^+$ abundance ratio correlates with variations in the $[O\,\text{iii}]/[O\,\text{iii}]$ strong line ratio. Thus, applying the empirical correction from Yates et al. (2020) ($Z_{Te; Y20}$) results in a trend more in line with $Z_{Te; SII}$. Additionally, we derive metallicity with four strong-line diagnostics ($R_{23}, N2O2, O3N2$ and $N2S2Ha$) using a mixture of observation- and theory-based calibrations. Spatial trends recovered by these strong-line methods again favour opposite trends to that of $Z_{Te; LS12}$, much more in line with those observed with $Z_{Te; SII}$ and $Z_{Te; Y20}$.

From diagnostic diagrams, we identify the presence of non-star-forming emission in the SAMI609396 system. We attribute this emission to shock-heated gas on the basis of the observed correlation between the $[S\,\text{ii}]/H\alpha$ emission line ratio and the measured velocity dispersion. Despite applying our analysis to the star-forming selected region around SAMI609396B, we note that in reality each spaxel will contain some amount of contaminating, non-star-forming emission. In particular, we show that spaxels in this star-forming selected region appear to form the beginning of a spatial mixing sequence, indicating spatial variations in the fractional contribution of non-star-forming emission to the total emission. Given the different ways metallicities from different diagnostics can be affected by contaminating emission, these variations could help to explain differences in the apparent metallicity trends recovered.

Aside from the $Z_{Te; LS12}$ application of the direct method, our metallicity measurements favour a flat metallicity gradient for SAMI609396B. This flat gradient can be explained by the effects of the merger which are known to produce flattened metallicity gradients due to inflow of pristine gas from large radii (Kewley et al. 2010). However, possible contamination from shock emission may affect the gradient measurement.

The direct method remains the main calibration baseline for studying the chemical evolution of galaxies. However, it is not immune to modelling uncertainties. This study highlights the importance of adequately constraining the internal ionisation and temperature structure within $\text{H}\,\text{ii}$ regions when probing spatial variations of the metallicity across galaxies. We have shown here that abundance measurements based on $T_e([O\,\text{iii}])$ alone are not a good indicator of the metallicity gradient in SAMI609396B due to their sensitivity to the ionisation parameter.

Spatially resolved applications of the direct method are currently limited even within the local Universe. Low-mass galaxies ($<10^9.5\ M_\odot$) contribute significantly to the stellar mass density and escape fraction of hydrogen ionizing photons at high redshift. However, the internal chemical distribution of these low-mass galaxies are rarely constrained owing to the spatial resolution and detection limit. This situation will be improved by forthcoming facilities such as JWST/NIRSpec and ground-based ELTs, which will push both the depth and spatial resolution attainable for IFU observations. In-depth analysis of local objects like SAMI609396B, thus set the stage for future detailed metallicity analysis of low-mass galaxies at high redshift.

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DATA AVAILABILITY

This paper uses data from the SAMI Galaxy Survey Public Data Release 2 (Scott et al. 2018) which are available at https://sami-survey.org/abdr. Those data products include strong emission line flux maps; the auroral emission line flux maps used here are available from the corresponding author (AJC) on reasonable request. A list of SAMI galaxies identified in our search as showing auroral line emission is given in Appendix A.

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to peak near the FoV boundary. It is likely that the region extending beyond the FoV contributes significantly to the global SFR of SAMI609396B. In that sense, we suggest that the quoted SFR can be considered as a lower-bound. In addition to SAMI609396B, we derive SFR for the more massive companion galaxy by summing the SFR map over the remainder of the SAMI FoV. This yields a value of SFR = 0.32 ± 0.08 M⊙ yr⁻¹, although we note that this spatial region exhibits significant contribution to its emission spectrum from non-star-forming sources which may bias this value (§ 5.2).

We derive global stellar mass values from g- and r-band photometry using the relation described in Section 4.2 of Bryant et al. (2015), based on stellar mass estimates from Taylor et al. (2011). We create a deblended segmentation map for the SDSS g-band imaging using detect_sources and deblend_sources from photutils package (Bradley et al. 2019). We use default values of 32 multi-thresholding levels and a blending contrast of 0.001 to run the deblending. The magnitudes obtained from these segmentation images are given in Table B1. Applying the Bryant et al. (2015) relation to those magnitudes we obtain stellar mass estimates of log(M⋆/M⊙) = 9.11 ± 0.10 for SAMI609396B and log(M⋆/M⊙) = 9.78 ± 0.10 for its more massive companion. The 0.10 dex uncertainties reflect the quoted 1-r scatter in this relation (Taylor et al. 2011). We ignore the flux uncertainties from the SDSS imaging as these contribute only 0.001 dex variations in stellar mass. These values correspond to a mass ratio of ~0.21 for this merger system. The global SFR and M∗ values derived here place SAMI609396B at least 1.3 dex above the star-forming main sequence (SFMS) for local star-forming galaxies (Renzini & Peng 2015).

APPENDIX C: SPECTRAL FITTING

The SAMI DR2 value-added release includes emission line maps for the most widely used strong optical lines. However, the primary focus of this work is the auroral emission lines, which are not included in these data products. Here we outline the methods behind our own spectral fitting to the SAMI DR2 data cubes. Flux measurements obtained here are used throughout § 3-4.

C1 Continuum Subtraction

For each spaxel in the reduced SAMI datacube, we fit the stellar continuum of the blue and red arms simultaneously using pPXF (Cappellari 2017). The 1D spectra for each spaxel are logaritmically rebinned. Given the different wavelength resolutions of the two arms, the higher resolution red arm is sampled down to match the velocity scale of the lower spectral resolution blue arm. Four moment fits are performed to the stellar continuum using the MILES library of stellar templates (Vazdekis et al. 2010). Two moment fits to the Balmer emission lines and strongest forbidden emission lines ([O iii] λ4959,5007, [N ii] λ6548,83 and [S ii] λλ6716,31) are included in the fitting procedure, however these derived emission line fluxes are discarded (refer to §C2 for emission line fitting).
SAM609396 exhibits strong emission lines with high equivalent-widths (>200 Å) and thus even spectra from individual spaxels feature many faint emission lines that are not widely studied. To ensure that the effect of these faint emission lines on the stellar template fitting is minimised, an iterative sigma-clipping method is employed (described in §2.1 of Cappellari et al. 2002).

In this approach, once a global minimum is found, spectral pixels deviating more than 3σ from this best-fit template are masked out and a new global fit is obtained. This process is repeated until no additional pixels are masked out. As a final step, the fits were visually inspected to ensure no spurious spectral features affected the fitting.

A continuum subtracted spectrum was obtained for each spaxel by subtracting the best-fitting stellar spectrum from the reduced observed spectrum from the SAMI data cube.

C2 Emission Line Fitting

Emission line maps of the most commonly used strong emission lines are provided in the value-added SAMI public release data. However, to ensure our emission line ratios are making self-consistent comparisons between strong-lines and the faint auroral lines, we perform new fits to these strong lines as well as the auroral lines. The emission line fitting procedure applied to each spaxel is as follows.

We first fit the Hα emission with a two-component Gaussian profile. We perform a χ²-minimisation fit across the 6672 – 6698 Å wavelength range (rest-frame 6553 – 6578 Å at SAMI609396B catalog redshift). This range encompasses >99% of the Hα emission for the redshift range covered by the spaxels of this object while minimising contribution from nearby [N ii] emission lines. The Hα emission is well modelled as a primary narrow component (median FWHMHα, nar = 2.26 Å, median redshift znar = 0.018566) and a secondary broad component (median FWHMHα, brd = 7.07 Å, median redshift zbrd = 0.018493) across the spatial extent of SAMI609396B.

We then fix the velocity and velocity dispersion for each spaxel by de-reddening each of these two kinematic components to values obtained from Hα and simultaneously fit across the full optical wavelength range for broad- and narrow-component fluxes for each of the strong emission lines ([O ii]λλ3726,9, Hβ, [O iii]λλ4959,5007, [O i]λ6300, [N ii]λλ6548,83, Hα, [S ii]λλ6716, and [S ii]λ6731).

The flux of each of these components is allowed to vary freely above a lower-bound of fcomp ≥ 0 with the exception of [O ii]λ6300 and [N ii]λ6548. The fluxes of each component of these lines are tied to the flux of the corresponding component of [O ii]λ5007 and [N ii]λ6583, respectively, according to following theoretical ratios: f5007 = 3 · f6300 and f6583 = 2.9 · f6548.

We calculate the uncertainty in the flux for each component by adding in quadrature the statistical error from the fit to an estimate of the uncertainty in the level of the continuum. This continuum uncertainty term is calculated as σf = σc · √N + EW/Δ (Eq. 1 in Pérez-Montero 2017) where σc is the standard deviation in a 30 Å range near the emission line, selected to contain only continuum flux, N is the number of spectral pixels encompassed by the fit Gaussian, EW is the equivalent width of the line, and Δ is the spec-
tral dispersion (Å/pixel). When considering the ‘total’ emission (i.e. sum of both components), the adopted uncertainty is the uncertainty of both components summed in quadrature.

With the exception of [O ′] λ46300, the faintest of these “strong-lines”, the fits to these strong lines achieve summed component $S/N > 20$ across the entire spatial extent of interest and achieve $S/N > 50$ in over 95% of the spaxels. The [O ′] λ46300 line fits achieve $S/N > 20$ in >95% of spaxels but only $S/N > 50$ in the brightest 8 spaxels. These two-component fits were visually inspected, adding confidence to the automated algorithms.

The fainter emission lines do not present with sufficient signal-to-noise to be reliably modelled with two-component fits. Instead, to these fainter lines we make single component fits where the velocity and velocity dispersion are fixed to those derived for the dominant narrow component above. The faint lines for which single components are used include the three auroral emission lines visually identified to be present ([S ′ ii] λ44069.76, [O ′ iii] λ4363, and [S ′ ii] λ43612), and the fainter Balmer emission lines Hδ and Hγ. Additionally, we include the [Fe ii] λ4360 emission line in our single component fit. The effect of the presence of this blended emission feature on the measured [O ′ iii] flux is discussed in detail in §C3.

As before, these emission line fluxes are allowed to vary freely with constraint of $f \geq 0$ except that fluxes of the [S ′ ii] λ44069.76 doublet are constrained such that $f_{4369} = 3 \cdot f_{4376}$. Uncertainties for each line are calculated in the same way as described for the individual components of the strong line fits described above. Once derived for each spaxel, these emission line fluxes are collated into 2D maps. Emission line fits for an example 1D spaxel spectrum are shown in Figure C1.

As a final step, we correct these 2D emission line flux maps using values from the extinction correction map provided in the SAMI DR2 data, derived using spatially smoothed Balmer decrements ($f_{Hα}/f_{Hβ}$) to account for aliasing effects introduced by the SAMI observing process (refer to Green et al. 2018 and Medling et al. 2018 for details), assuming a Cardelli et al. (1989) extinction law with $R_V = 3.1$. Unless otherwise specified, the analysis of this paper is conducted using these reddening corrected emission line flux maps.

**C3 [Fe ii] λ4360 & [O ′ iii] λ4363 blending**

Several recent studies have identified an emission feature at λ4360 Å which may be blended with the [O ′ iii] λ4363 emission line, attributed to an [Fe ii] emission line (Curti et al. 2017, Berg et al. 2020; Arellano-Córdoa & Rodríguez 2020). From visual inspection of 1D spectra, we identify that [O ′ iii] λ4363 emission often presents with an extended blue wing, which we attribute to blending with this [Fe ii] λ4360 line.

We account for this by including an emission feature at this wavelength in our line-fitting routine whose flux is allowed to vary freely (Appendix C2). As with all faint lines in the line-fitting, the velocity and velocity dispersion is tied to that of the narrow component identified for Hα. Visually, the fits obtained appear to model the emission features around λ4363 Å well. The median ratio between the [O ′ iii] and [Fe ii] lines across the spatial extent with $S/N_{λ4363} > 3$ is $f_{4363}/f_{4360} = 2.1$ with standard deviation $σ_{4363/4360} = 1.47$.

As a check of how reliable our [O ′ iii] flux measurements with this blended [Fe ii] + [O ′ iii] profile are, we fit this wavelength region using three approaches and compare the results. The three approaches are:

(i) **Standard fitting**: As described in Appendix C2 where [Fe ii] and [O ′ iii] components are simultaneously fit for.
(ii) **Naïve single component**: A simple single component fit to [O ′ iii] across the wavelength range from 4345 – 4380 Å. No attempt is made to account for [Fe ii] emission.
(iii) **Red wing single component**: A single component is fit to [O ′ iii], excluding pixels blueward of $λ = 4362.5 \times (1 + z_{HI})$, where $z_{HI}$ is the redshift value obtained from the narrow-component fit to Hα for the spaxel in question. This should mask out spectral pixels with $> 5 \%$ contribution from [Fe ii] emission.

In each approach, the velocity and velocity dispersion values are fixed to those obtained for the Hα narrow component, as in our standard fitting. The best-fit profiles from each of these approaches are shown in the top panel of Figure C2. The bottom panel shows the distribution of values obtained for $f_{alt}/f_{std}$ ratios, where $f_{std}$ is the [O ′ iii] flux obtained from method (i) and $f_{alt}$ is the flux from approaches (ii) and (iii). As expected, when no attempt is made to account for [Fe ii] emission as in method (ii), the [O ′ iii] flux is systematically underestimated by around 10% ($f_{alt}/f_{std} =$...
1.09 ± 0.04; orange dash-dotted line in bottom panel of Figure C2). However, when applying method (iii), where the blue wing of [O ii] is masked out, we see no significant systematic offset from our values obtained by method (i) \( f_{\text{blue}}/f_{\text{red}} = 0.99 ± 0.07; \) purple dashed line in bottom panel of Figure C2. We note that there is large scatter in the distribution of \( f_{\text{blue}}/f_{\text{red}} \) for this latter case. This uncertainty of \( >10\% \) is not unreasonable for observations with \( S/N \sim 3 - 15 \). We note also that when using these auroral line fluxes to derive electron temperature measurements, measurement uncertainties of this level are likely outweighed by modelling uncertainties (refer to § 3).

From this we conclude that for the \([O\text{ ii}] / [Fe\text{ ii}]\) flux ratios we observe \((f_{3865}/f_{3460} - 2.1)\), on average methods (i) and (iii) each suffer minimally from contamination by this blended emission feature at \( f_{4360}. [O\text{ ii}] / f_{4465} \) flux measurements quoted in other sections are those derived from the standard fitting routine (method (i)).

**APPENDIX D: IMPLEMENTING THE METHOD OF YATES ET AL. (2020)**

Measurements of electron temperature \((T_e)\) are highly sought after in chemical abundance studies as they enable “direct-method” metallicity measurements to be made. Full application of the direct method to determine the total oxygen abundance requires measurements of both \( T_e([O\text{ ii}]) \) and \( T_e([O\text{ iii}]) \), such that both \( O^+H^+ \) and \( O^+H^+ \) can be determined. However, given the faintness of the required auroral emission lines, often only \( T_e([O\text{ iii}]) \) can be measured directly. In this case, it is common to apply a “semi-direct” method. In this approach, the \( T_e([O\text{ iii}]) \) is indirectly determined from the measured \( T_e([O\text{ ii}]) \) via some assumed relation, allowing the \( O^+ \) abundance to be derived.

While it is common to assume a simple positive correlation between \( T_e([O\text{ ii}]) \) and \( T_e([O\text{ iii}]) \) (e.g. Izotov et al. 2006; López-Sánchez et al. 2012; Yates et al. 2020 (Y20 hereafter)) find that this does a poor job of describing the observed scatter about this relation. Instead, Y20 highlight that at fixed metallicity, \( T_e([O\text{ iii}]) \) is anti-correlated with \( T_e([O\text{ ii}]) \), and that the general positive trend between \( T_e([O\text{ ii}]) \) and \( T_e([O\text{ iii}]) \) is due to the fact that both correlate negatively with metallicity and in general will both be higher in lower metallicity systems.

Based on these observations, Yates et al. 2020 have outlined a new method for determining \( T_e([O\text{ iii}]) \) and metallicity in systems where only \( T_e([O\text{ ii}]) \) can be directly measured. Unlike previous semi-direct methods, in the Y20 method, \( T_e([O\text{ ii}]) \) and metallicity are solved for simultaneously. This differs from previous semi-direct methods in which \( T_e([O\text{ iii}]) \) is usually determined based on \( T_e([O\text{ ii}]) \) independently of metallicity. Metallicity is then subsequently determined using the value obtained for \( T_e([O\text{ iii}]) \).

We note that this method (“Y20 method”) is separate to the empirical correction described in that same publication which we performed in § 4.1.2 (“Y20 correction”), and the Y20 empirical correction still needs to be applied to the metallicities arising from the Y20 method.

In Section 4 we applied a simple semi-direct method to our SAMI609396B data in which \( T_e([O\text{ iii}]) \) was determined from \( T_e([O\text{ ii}]) \) using the calibration of López-Sánchez et al. 2012 (Eq. 6 in § 4.1) and then the metallicity subsequently determined accordingly (that method was referred to as \( Z_{T_e;\text{LS12}} \) throughout this work). Here, we additionally apply the Y20 method to our SAMI609396B data. We find the results of the Y20 method to be double-valued (Figure D1). The “upper branch” largely agrees with our \( Z_{T_e;\text{LS12}} \) metallicities within \( -0.15 \) dex (median absolute offset is 0.06 dex), however the “lower branch” gives starkly different values. Spatial metallicity trends arising from each branch of this method differs noticeably (Figure D2), making it difficult to draw conclusions without further characterisation of the behaviour of each branch in a larger data set. We describe the details of our implementation of the Y20 method below.

**D1 Basis of the Yates Method**

The Y20 method differs from other semi-direct methods in that \( T_e([O\text{ iii}]) \) and metallicity \((Z_{T_e})\) are evaluated simultaneously in order to account for the interdependence of these parameters at fixed \( T_e([O\text{ ii}]) \); whereas typically semi-direct methods have involved inferring a \( T_e([O\text{ iii}]) \) value from a \( T_e([O\text{ ii}]) \) measurement via a fixed relation and then subsequently determining the metallicity using this value.

The Y20 method centres on a metallicity-dependent fit to the \( T_e([O\text{ iii}]) - T_e([O\text{ ii}]) \) relation, outlined as follows:

\[
T_e([O\text{ iii}]) = \frac{a(Z_{T_e})^2}{2 \cdot T_e([O\text{ ii}])}, \tag{D1}
\]
where

\[ a = -12030.22 \cdot Z_{Te} + 113720.75. \]  

(D2)

This can be solved simultaneously with the following equations which determine oxygen abundance from measured [O\text{\,iii}]/H\alpha and [O\text{\,iii}]/H\beta line ratios given values for \( T_e([\text{O\,iii}]) \) and \( T_e([\text{O\,iii}]) \):

\[
O^+ / H^+ = \frac{[\text{O\,iii}]/\lambda 13726, 29}{H\beta} \frac{g_1 \alpha H\alpha} {\sqrt{T_e([\text{O\,iii}])}} \times \exp\left[E_{12}/kT_e([\text{O\,iii}]\right)] \times \frac{\beta}{E_{12} T_{12}} \tag{D3}
\]

\[
O^{++} / H^+ = \frac{[\text{O\,iii}]/\lambda 4959, 5007}{H\beta} \frac{g_1 \alpha H\alpha} {\sqrt{T_e([\text{O\,iii}])}} \times \exp\left[E_{12}/kT_e([\text{O\,iii}]\right)] \times \frac{\beta}{E_{12} T_{12}} \tag{D4}
\]

\[
Z_{Te} = 12 + \log(O^+ / H^+ + O^{++} / H^+). \tag{D5}
\]

The reader is referred to Yates et al. (2020) and Nicholls et al. (2014) for more details on these equations including the values and calculations of various parameters used.

D2 Two-valued solution of the Yates method

In Yates et al. (2020), the authors propose solving these equations with fixed point iteration, however we instead propose numerically solving for the intersection of equations D1 & D5. This preference is based on our observation that the relations described in Equations D1 & D5 in fact yield two solutions within the range of what could be considered physically reasonable.6 This is illustrated in Figure D1 for an example typical SAMI609396B spaxel with \( T_e([\text{O\,iii}]) = 10^4 \) K, and [O\text{\,iii}]/H\beta and [O\text{\,iii}]/H\beta line ratios of 3.54 and 2.42 respectively. For this example spaxel it can be seen that two possible solutions exist: (1) at \( T_e([\text{O\,iii}]) = 9.342 \) K and \( Z_{Te} = 8.31 \), and (2) at \( T_e([\text{O\,iii}]) = 14,662 \) K and \( Z_{Te} = 8.03 \). Neither of these solutions is physically plausible and while solution (1) would fall in a more densely populated region of the \( T_e([\text{O\,iii}]) \) - \( Z_{Te}([\text{O\,iii}]) \) relation as shown in Yates et al. (2020) (refer to Figure 5 in that paper), observed points comparable to solution (2) are found in their sample too. Indeed, beyond the single example shown in Figure D1, we find that all spaxels in SAMI609396B with at least one solution have precisely two. How then should we decide which of these two solutions to adopt?

The blue open circle in Figure D1 shows that the \( T_e([\text{O\,iii}]) \) obtained via the López-Sánchez et al. (2012) \( T_e([\text{O\,iii}]) - T_e([\text{O\,iii}]) \) relation (refer to Eq. 6 in § 4.1) agrees quite well with the lower valued \( T_e([\text{O\,iii}]) \) solution. However, this disregards the point of the \( Y20 \) method and findings presented in this work: that assuming a simple fixed relationship between \( T_e([\text{O\,iii}]) \) and \( T_e([\text{O\,iii}]) \) can be misleading.

The \( Y20 \) iterative method as originally applied in Yates et al. (2020) selects for the “lower branch” (red circle in Fig D1). However, subsequent application of the \( Y20 \) correction serves to shift this point to a slightly higher metallicity, partly toward the upper branch solution (green open circle in Fig D1).

To investigate this further, the original \( Y20 \) sample was revisited with the two-valued solution in mind (Yates 2020; private communication). It was found that targets where the direct7 metallicity was closer to the “upper branch” solution were often targets with an \( O32 \) value below the threshold value for which the \( Y20 \) correction should be applied (\( O32 \leq 0.29 \)). Thus, this \( O32 \) threshold could be used to distinguish between the lower and upper branches. All spaxels across the spatial extent of SAMI609396B fall in this category with \( O32 \leq 0.29 \) (refer to Fig 8), meaning we would adopt the upper branch value under this scheme, rather than the lower branch value favoured by the original iterative implementation.

While we do not directly measure \( T_e([\text{O\,iii}]) \), in § 3.3 we derived \( T_e([\text{S\,i}]) \) from the \([\text{S\,i}]\) \( \lambda 4069, 76 \) line ratio (refer to Figure 4). Panel (c) of Figure 4 shows that \( T_e([\text{S\,i}]) < T_e([\text{O\,iii}]) \) across the majority of spaxels in SAMI609396B, with a median value of \( T_e([\text{S\,i}]) = 9,295 \) K. Given that previous studies have found that \( T_e([\text{S\,i}]) \) and \( T_e([\text{O\,iii}]) \) are often in general agreement (e.g. Croxall et al. 2016), we consider that this additionally supports our selection of the upper-branch value. We note, however, that large scatter is known to exist in both the \( T_e([\text{S\,i}]) - T_e([\text{O\,iii}]) \) and \( T_e([\text{O\,iii}]) \) \(- T_e([\text{O\,iii}]) \) relations.

D3 Comparison between Y20 method and LS12 method

In line with our methods outlined in Appendix D2 above, we consider two versions of the \( Y20 \) method: one in which we adopt the “upper branch” solution to the \( Y20 \) method, and another where we adopt the “lower branch” and apply the \( Y20 \) empirical correction. We find that the resulting \( T_e([\text{O\,iii}]) \) and \( Z_{Te} \) maps are smooth with no unexpectedly large variations observed between pairs of adjacent spaxels.

In Figure D2 we compare the metallicities obtained from these \( Y20 \) methods with those obtained in § 4.1 from the \( Z_{Te} \), LS12 method. Metallicity maps and spatial trends in the far- and centre-left columns of Figure D2 are simply reproduced from Figure 5 and show the \( Z_{Te} \), LS12 method with and without the \( Y20 \) empirical correction. The centre-right column shows the \( Y20 \) upper branch metallicities, while the far-right column shows corrected \( Y20 \) lower branch metallicities (additionally, the uncorrected lower branch metallicity trend is shown in panel h as the magenta dotted line).

We first note that, even after the \( Y20 \) correction, the lower branch metallicities are significantly lower than any of our other semi-direct methods.8 The large scatter in the values obtained makes it difficult to determine the spatial metallicity trend from this method, however, qualitatively it does seem to be broadly consistent with the trend seen in the \( Z_{Te} \), LS12 method applied in § 4.1.2.

The normalisation of the upper branch values is in much better agreement with other semi-direct methods. The effect on the spatial trend is less clear: it appears somewhat flattened compared to \( Z_{Te} \), LS12 - however if a gradient were to be computed it would

6 More generally, it is possible that for some observations there will be no solution. In these cases, solving via the iterative method may be preferable (Yates 2020; private communication)

7 Here “direct” metallicity refers to a metallicity in which both \( T_e([\text{O\,iii}]) \) and \( T_e([\text{O\,iii}]) \) have been directly measured with auroral lines.

8 And, indeed, strong-line methods; although some degree of offset is expected there (e.g. Kewley & Ellison 2008)
likely depend strongly on a cluster of lower metallicity points with projected distance $r \approx 0$ kpc.

Yates et al. (2020) showed that the semi-direct abundance deficit at low $O^{++}/O^+$ (which the Y20 correction aims to address) is present across all $T_e([O\,\text{II}]) - T_e([O\,\text{III}])$ relations considered in that work, including LS12 (Figure 6 in Yates et al. 2020). In particular, they show in detail its effect on the Y20 lower branch metallicities. Although it seems that low $O^{++}/O^+$ values seem to correlate with an increased preference for the upper branch metallicity solution, it is currently unclear whether variations in $O^{++}/O^+$ result in semi-direct metallicity biases in a similar way to that observed by Yates et al. (2020) with respect to the lower branch solution and other $T_e([O\,\text{II}]) - T_e([O\,\text{III}])$ relations. In the context of SAMI609396B where we have shown large scale variations in the $[O\,\text{II}]/[O\,\text{III}]$ ratio, the existence of such a bias could affect our interpretation of the spatial metallicity trend resulting from this upper branch solution. Addressing this issue would require a more detailed analysis of a more extensive sample (e.g. the Yates et al. (2020) sample) and is beyond the scope of this paper.

In summary, we find that the Y20 semi-direct method as originally proposed favours a similar spatial gradient to that of $Z_{Te; Y20}$ after the application of the Y20 correction, albeit at a much lower normalisation. After identifying the two-valued nature of these relations, we found that adopting the upper branch values resulted in normalisation that agreed much better with other methods. We defer commenting on the spatial trend arising from these upper branch values to a later study, after the two-valued nature of the Y20 relations has been examined in more detail.

Overall, these findings do not alter the main conclusion of this work: that assumptions around the temperature structure of H\textsc{ii} regions can have a significant impact on measured spatial metallicity trends in IFU observations of galaxies.

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