

DUVET: Resolved direct metallicity measurements in the outflow of starburst galaxy NGC 1569

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ABSTRACT

We present the results of direct-method metallicity measurements in the disc and outflow of the low-metallicity starburst galaxy NGC 1569. We use Keck Cosmic Web Imager observations to map the galaxy across 54'' (800 pc) along the major axis and 48'' (700 pc) along the minor axis with a spatial resolution of 1'' (~15 pc). We detect common strong emission lines ([O III] λ 5007, H β , [O II] λ 3727) and the fainter [O III] λ 4363 auroral line, which allows us to measure electron temperature (T_e) and metallicity. Theory suggests that outflows drive metals out of the disc driving observed trends between stellar mass and gas-phase metallicity. Our main result is that the metallicity in the outflow is similar to that of the disc, $Z_{\text{out}}/Z_{\text{ISM}} \approx 1$. This is consistent with previous absorption line studies in higher mass galaxies. Assumption of a mass-loading factor of $\dot{M}_{\text{out}}/\text{SFR} \sim 3$ makes the metal-loading of NGC 1569 consistent with expectations derived from the mass–metallicity relationship. Our high spatial resolution metallicity maps reveal a region around a supermassive star cluster (SSC-B) with distinctly higher metallicity and higher electron density, compared to the disc. Given the known properties of SSC-B the higher metallicity and density of this region are likely the result of star formation-driven feedback acting on the local scale. Overall, our results are consistent with the picture in which metal-enriched winds pollute the circumgalactic medium surrounding galaxies, and thus connect the small-scale feedback processes to large-scale properties of galaxy haloes.

Key words: galaxies: NGC 1569 – galaxies: abundances – galaxies: evolution – ISM: jets and outflows.

1 INTRODUCTION

Galaxy scale winds (or outflows) play a key role in galaxy evolution by redistributing baryons from the disc of star-forming galaxies (e.g. Chevalier & Clegg 1985; Heckman, Armus & Miley 1990). Galactic winds are widely observed in star-forming galaxies (Veilleux, Cecil & Bland-Hawthorn 2005; Veilleux et al. 2020), and are frequently invoked in galaxy evolution theory to explain a number of observations, such as the stellar mass function of galaxies (e.g. Pillepich et al. 2018)

and the metal content of the circumgalactic medium (e.g. Tumlinson, Peeples & Werk 2017; Péroux & Howk 2020). Despite their critical importance for theory, properties of outflows, like the metallicity and electron density, remain unconstrained.

Outflows likely play a key role in redistributing metals in galaxies. All metals are created during the many stages of stellar evolution, in the galaxy disc, and yet metals make up a significant mass component of the gaseous haloes of galaxies (e.g. Werk et al. 2013). Outflows containing metals originating from supernovae ejecta and entrained ISM gas offers an obvious mechanism to enrich haloes (Peeples & Shankar 2011; Christensen et al. 2018). Moreover, the relationship between total galaxy stellar mass and metallicity (MZR) shows that

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lower-mass galaxies have lower metallicities (e.g. Tremonti et al. 2004; Berg et al. 2012; Kirby et al. 2013). Most galaxy evolution models and simulations incorporate stellar feedback (e.g. Springel & Hernquist 2003; Oppenheimer & Davé 2006; Hopkins et al. 2014) as a mechanism to decrease ISM metallicities in low-mass galaxies. This process is quantified by the metal-loading factor, ζ , which describes how efficient outflows are at removing metals from the ISM relative to how many metals are retained due to star formation (Peeples & Shankar 2011):

$$\zeta = \frac{Z_{\text{out}} \dot{M}_{\text{out}}}{Z_{\text{ISM}} \text{SFR}}. \quad (1)$$

Z_{out} and Z_{ISM} are the outflow and ISM metallicities, respectively, \dot{M}_{out} is the mass outflow rate, and SFR is the star formation rate. Observational constraints on $Z_{\text{out}}/Z_{\text{ISM}}$ of galaxies across a wide range of galaxy properties are needed to determine if this process is sufficient to shape the MZR.

To measure $Z_{\text{out}}/Z_{\text{ISM}}$, one must measure the metallicity in both the ISM and the outflow from the galaxy. While substantial literature exists characterizing the gas-phase metallicity within galaxies and the mass-loading of outflows (reviewed in Veilleux et al. 2020), there is a lack of constraints on the metal content outside the galactic mid-plane. Gas-phase metallicity measurements are usually determined using optical emission lines to estimate the O/H abundance of the gas as a proxy for metallicity.

The ‘strong line’ method (e.g. Kewley, Nicholls & Sutherland 2019; Maiolino & Mannucci 2019) estimates metallicity indirectly using the ratio of strong emission lines (e.g. $[(\text{O II}) \lambda 3727 + (\text{O III}) \lambda 5007]/\text{H}\beta$), calibrated either empirically to H II regions in discs or using photoionization models. We must note that metallicities measured from different methods have been shown to differ up to 0.7 dex (Kewley & Ellison 2008; Maiolino & Mannucci 2019). The strong-line method is very useful for estimating metallicities in the ISM; however, it is unsuitable for measuring metallicity in outflows because it is calibrated primarily in H II regions where physical conditions differ substantially from outflows. Indeed, using strong-lines may not only be unreliable, but would lead to misleading outflow metallicities.

The ‘direct method’ uses the ratio of auroral to strong lines (like $[\text{O III}] \lambda 4363/[\text{O III}] \lambda 5007$) to measure the electron temperature (T_e) of the gas. It is then possible to infer metallicity, assuming that metals dominate the cooling of the gas (Berg et al. 2012; Pérez-Montero 2017). In this method, minimal assumptions on the photoionization source are made. T_e -based metallicities are, therefore, a more reliable way to determine outflow metallicities. Auroral lines, however, are typically 50–100 times fainter than H β , making them challenging to observe in intrinsically faint outflows. Moreover, they are only sufficiently bright in high-temperature/low-metallicity environments. Therefore, while the direct method does open a window to measuring the metallicity of outflows, it is only feasible in low-metallicity galaxies.

Alternatively, outflow metallicity can be inferred via X-rays of the hot phase of the outflowing gas. The hot phase gas has been observed for both NGC 1569 (Martin, Kobulnicky & Heckman 2002) and M 82 (Lopez et al. 2020) to be significantly metal-enriched by a factor of $\sim 3.5 \times$ that of the disc. This is expected as hotter gas in outflows likely originates from the supernovae ejecta, while colder phases more likely probe entrained gas from the ISM. The colder phases of the outflow can be probed via metal absorption lines. Chisholm, Tremonti & Leitherer (2018) use this method to determine the metallicity in the outflow of seven galaxies with stellar masses spanning 10^7 – $10^{11} M_{\odot}$. Using direct-method gas-phase abundances,

they found an inverse correlation between $Z_{\text{out}}/Z_{\text{ISM}}$ and stellar mass, showing that outflows in low-mass galaxies are more enriched in relation to their host galaxy. They show that these results can reproduce the MZR, under a set of assumptions described in that work.

More recently, Cameron et al. (2021) pioneered a self-consistent study of the metal content throughout the baryon cycle using direct-method abundances in the disc, inflow, and outflow of Mrk 1486. They observed an $Z_{\text{out}}/Z_{\text{ISM}} \approx 1.6$. This emission line metal ratio is only half that of the absorption-line value from Chisholm et al. (2018) for the same galaxy. This would suggest that absorption-line methods may overestimate Z_{out} relative to emission-line based metallicity, however, the systematics of comparing absorption-line to emission-line methods remain poorly known. Clearly, more work is needed to robustly constrain the metallicity of outflows.

In this work, we extend the pioneering method of Cameron et al. (2021) to galaxy NGC 1569. NGC 1569 is a well-studied, nearby (3.25 Mpc, Tully et al. 2013), low metallicity ($12 + \log(\text{O}/\text{H}) = 8.19$, Kobulnicky & Skillman 1997), low mass ($\log(M_{\star}/M_{\odot}) = 8.6$, Leroy et al. 2019), and starburst galaxy. It has two supermassive star clusters (SSCs) that formed after a period of high star formation approximately 10 Myr ago (Hunter et al. 2000). H α emission shows a complex structure around the SSCs, with filaments and bubbles suggesting a stellar feedback driven outflow (Heckman et al. 1995; Westmoquette et al. 2007). Analysis of the H I kinematics suggests a mass loading of the cold gas in the wind of $\dot{M}_{\text{out}}/\text{SFR} \sim 3$ (Johnson et al. 2012; McQuinn, van Zee & Skillman 2019). X-ray observations show evidence of a metal enriched outflow (Martin et al. 2002). Due to its proximity, low gas-phase metallicity, and observed metal-enriched outflows, NGC 1569 provides an excellent laboratory for resolving the metallicity of a galactic wind.

The remainder of this paper is organized as follows: We present Keck/KCWI observations of NGC 1569 in Section 2. Section 3 describes our spectral analysis, including our line-fitting method (subsection 3.1), emission-line maps (subsection 3.2), and separation of the disc and outflow regions (subsection 3.3). We then use the emission-line maps to examine the electron temperature and metallicity maps in Section 4 and discuss possible temperature fluctuations in Section 5. We use these results to examine the outflow of NGC 1569, focusing on the T_e fluctuations in Section 6, the density in Section 7, and metal loading in Section 8. Finally, we present our summary in Section 9. We assume a flat Λ CDM cosmology with $H_0 = 69.3 \text{ km Mpc}^{-1} \text{ s}^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$.

2 OBSERVATIONS AND DATA REDUCTION

We observed NGC 1569 at three different positions with Keck/KCWI, as part of the Deep near-UV observations of Entrained gas in Turbulent galaxies (DUVET) survey. We targeted two positions aimed at the galaxy disc, and a third position towards the minor axis. The minor axis frame is co-located with an H α filament. Fig. 1 shows an *HST* composite image. The white dashed lines in the figure illustrate the position of the major and minor axes, which intersects at the centre of *Spitzer*/IRAC 3.6 μm band observations. We also show the position of our three KCWI pointings. NGC 1569 has an inclination of 60° measured from H I observations (Stil & Israel 2002). Typical of dwarf galaxies, the light of the galaxy is not symmetric. The derived inclination may, therefore, have significant uncertainty. Our field-of-view covers a projected distance of ~ 700 pc along the minor axis. Considering an inclination of 60° this corresponds to a distance of ~ 810 pc from the galaxy mid-plane. If we consider that the galaxy is less inclined, 50° for

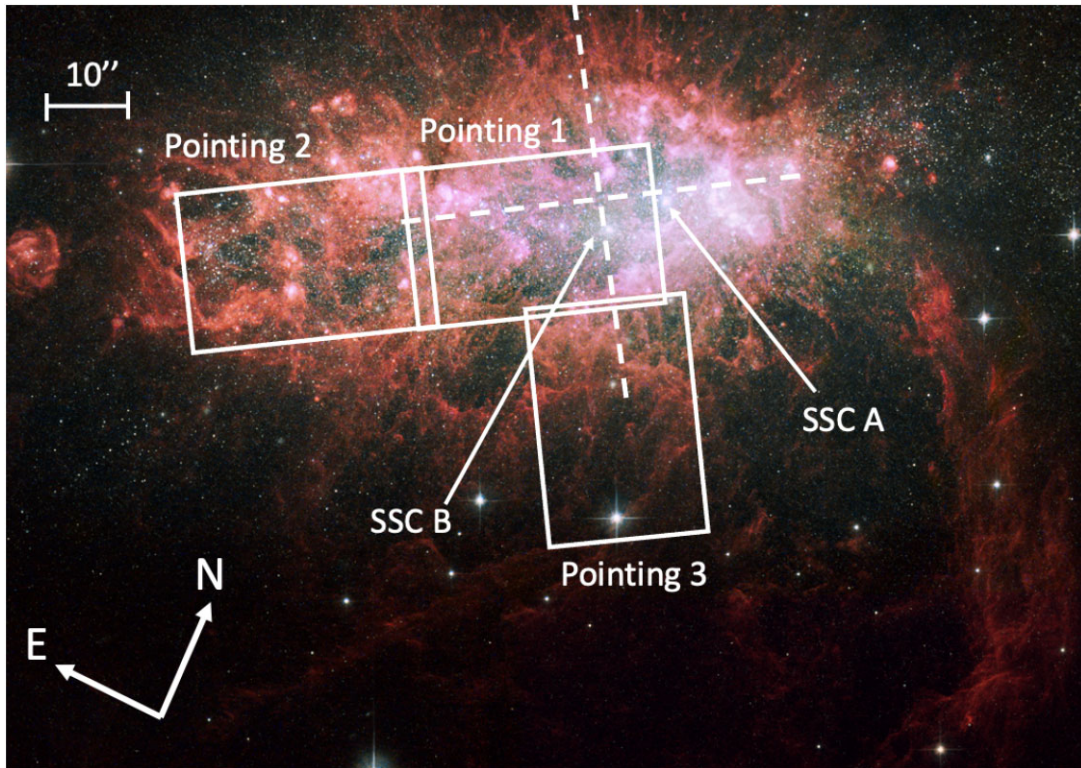


Figure 1. *HST* composite image of NGC 1569, red: F658N filter ($H\alpha + [N\text{II}]$), green: F606W filter, light blue: F5002N filter ($[O\text{III}]$), and dark blue: F487N filter ($H\beta$). Plotted on top of the *HST* image are our three KCWI positions. Our KCWI data maps $54''$ (~ 800 pc) across the major axis and $48''$ (~ 700 pc) (\sim across the minor axis). The arrows show the position of the two known super star clusters (SSC) SSC A and SSC B. The two dashed lines show the major and minor axis of the galaxy obtained from *Spitzer*/IRAC $3.6\ \mu\text{m}$ band observations.

example, the distance could be ~ 915 pc. Throughout this work, we report projected distances.

The KCWI observations were conducted on 2020 November 14, with a mean seeing of $1.2''$. All observations used the large IFU slicer. The field of view of each individual frame is $20'' \times 33''$ with a spaxel size of $0''.29 \times 1''.35$. We used two different configurations of the blue medium-dispersion grating to observe each pointing. The first setting is centred at $4050\ \text{\AA}$ ('blue' setting) and the other at $4700\ \text{\AA}$ ('red' setting). These configurations gave us a total continuous wavelength range of $3600\text{--}5130\ \text{\AA}$, with a spectral resolution of $R \sim 2000$. We used half-slice dither in both configurations to increase the spatial sampling. Our observation strategy and reduction methods are described in the literature for other DUVET targets (Cameron et al. 2021; McPherson et al. 2023).

To avoid saturation on bright emission lines such as $[O\text{III}]\ \lambda 5007$, each position was observed with short exposures while long exposures were used to detect fainter lines like $[O\text{III}]\ \lambda 4363$. Pointing 1 was observed with seven exposures in the red setting (3×30 s, 3×100 s, and 1×300 s) and four in the blue setting (1×30 s and 3×100 s). Pointing 2 was observed with six exposures in the red setting (3×30 s and 3×300 s) and four in the blue setting (1×100 s and 3×300 s). Pointing 3 was observed with six exposures in the red setting (3×30 s and 3×300 s) and three in the blue setting (3×300 s). We also obtained sky fields for the blue and red settings of 300 s exposure each.

To reduce observations we used the KCWI Data Extraction and Reduction Pipeline v1.1.0.¹ To ensure clean spectra from the galaxy,

we executed a sky subtraction using the sky frame previously described. Offset skies are scaled to match science exposure times. Flux calibration was performed within the pipeline using the standard star Feige25. Prior to combining individual exposures, we aligned individual cubes for each pointing by minimizing the residual in the $H\gamma$ emission line, which is observed in both the red and blue settings and in all pointings. This was carried out to account for any possible small shifts in the spatial coordinates. We combined long and short exposures using the $[O\text{III}]\ \lambda 5007/\lambda 4959$ ratio as an indicator of saturation. Assuming a value of 3 (Osterbrock & Ferland 2006) we determine spaxels for which $[O\text{III}]\ \lambda 5007$ was saturated. For those spaxels, we replaced $[O\text{III}]\ \lambda 5007$, $[O\text{III}]\ \lambda 4959$, and $H\beta$ in long exposures with short exposures in a $20\ \text{\AA}$ wavelength region centred on the emission line. This procedure is discussed in more detail in McPherson et al. (2023).

Exposures were reprojected into $0.29'' \times 0.29''$ spaxels and co-added using the python package MONTAGE.² We then binned our cubes in 3×3 spaxels to have a spaxel size of $0.87'' \times 0.87''$, which is approximately half of the FWHM of our point spread function. After co-addition and re-binning of frames, several small differences between red and blue settings and positions needed to be accounted for to generate a uniform data set.

First, a small difference in continuum surface brightness was present between the red and blue settings. This is likely due to imperfections in flux calibration. We scaled the blue spectrum in each spaxel by the average ratio observed in the overlapping wavelength range between the two gratings, which was between 4250 and

¹<https://github.com/Keck-DataReductionPipelines/KcwiDRP>

²<http://montage.ipac.caltech.edu/>

4500 Å. This scaling was of order ~ 1 per cent of the flux. We then combined blue and red cubes for each pointing.

Secondly, to spatially align the three pointings shown in Fig. 1, we used $H\gamma$ flux in the overlapping regions between the pointings. We iteratively shift the position of each pointing by integer spaxels in all directions and minimize the residual of $\Delta f_{H\gamma}$ between the two positions.

Finally, we account for small differences in fluxes between pointings. Pointing 1 was observed directly after the flux standard. We, therefore, assume it is best calibrated pointing. We compared the shape of the continuum in the overlapping regions between Pointings 1 and 2, as well as between Pointings 1 and 3. We then fitted a polynomial to the average shift of all overlapping spaxels and shifted the spectra in all spaxels in Pointing 2 and Pointing 3 by the corresponding polynomial. This change is likewise of order ~ 1 per cent, or less, of the continuum flux.

2.1 Continuum subtraction

Milky Way extinction is corrected using the Cardelli, Clayton & Mathis (1989) extinction law, with extinction $A_v = 1.85$ (Schlafly & Finkbeiner 2011). Then we corrected for the stellar continuum. For continuum fitting we implement the standard method via pPXF (Cappellari 2017), with model spectra sourced from the Binary Population and Spectral Synthesis code v2.3 (BPASS v2.3). The BPASS templates contain single and binary stars with an initial mass function extending between 0.1 and $300 M_\odot$. Prior to running the continuum fit, we masked all visually identifiable emission lines in a 200 km s^{-1} window.

Our observations include both regions with significant stellar continuum (Pointing 1 & 2) and those with minimal contribution from the continuum (Pointing 3). Modelling the stellar continuum is a non-linear process, and to do so in regions of low-S/N would likely result in incorrect adjustments to the spectrum. To determine which spaxels have sufficient stellar continuum, we computed the continuum signal-to-noise ratio (S/N) in a band of 200 Å , ranging from 4600 to 4800 Å . While faint emission exists, the integrated flux in this band is heavily dominated by continuum. The fitting was performed only in spaxels where the signal-to-noise ratio (S/N) of the continuum was greater than 3. For spaxels with a continuum signal-to-noise ratio lower than 3, we fit a constant value to represent the continuum.

3 SPECTRAL ANALYSIS

3.1 Emission line fitting

For the emission line fitting we used our internal software, `threadcount`³, built on work done by Reichardt Chu et al. (2022). This software allows for the user to input multiple models with different numbers of Gaussians and different constraints. The software automatically selects the best model based on the Bayesian Information Criterion (BIC), given a ΔBIC threshold. To calculate the uncertainties in emission line fluxes, `threadcount` employs Monte Carlo simulations. It generates simulated spectra by adjusting the observed flux in each spectral pixel using a normal distribution with a standard deviation derived from the observed variance in our data. The uncertainty in the flux is then computed as the standard

deviation of the measured fluxes in the simulated spectra. For this study, 100 simulations for each spaxel were performed.

We first fitted the $H\beta$ and $H\gamma$ emission lines using a single Gaussian model. We corrected for the galaxy internal dust extinction based on the $H\beta/H\gamma$ flux ratio. We assumed an intrinsic value of $f_{H\beta}/f_{H\gamma} = 2.12$, which is typical for gas at a temperature of about 10^4 K (Osterbrock & Ferland 2006). As NGC 1569 is a low metallicity galaxy, we used the extinction law from the Large Magellanic Cloud from Gordon et al. (2003) with $R_v \approx 2.7$. We found an average extinction of $A_v = 1.2$ on the disc and an average of $A_v = 1.5$ in the outflow.

We fitted the $H\beta$ and $[\text{O III}] \lambda 5007$ lines using single Gaussian models, we do not see evidence of double Gaussian emission. For the $[\text{O II}] \lambda \lambda 3726,9$ doublet, we used a double Gaussian model with a constrained shift between the centroids but no constraint on the flux ratios.

The $[\text{O III}] \lambda 4363$ line can be blended with emission from $[\text{Fe II}] \lambda 4360$. This has been observed in stacked galaxy spectra and H II regions (Curti et al. 2017; Berg et al. 2020; Rickards Vaught, Sandstrom & Phangs Team 2023). We observe $[\text{Fe II}]$ in some spaxels in our KCWI data, but most spaxels do not show any significant detection. The bottom panels of Fig. 2 show three examples of $[\text{O III}] \lambda 4363$ emission lines from our data. In panel (a), we show an example where no $[\text{Fe II}]$ contamination is observed, panel (b) shows an example with a small $[\text{Fe II}]$ detection, and panel (c) shows the strongest $[\text{Fe II}] \lambda 4360$ detection.

In order to account for possible contamination by $[\text{Fe II}] \lambda 4360$, we fitted the $[\text{O III}] \lambda 4363$ emission with two models: a single Gaussian and a double Gaussian with a fixed shift between the centroids. We determined the best model by performing a BIC test. A ΔBIC value of 10 is typically considered significant evidence against the single Gaussian model (Kass & Raftery 1995; Swinbank et al. 2019). However, for some astrophysical applications, a higher ΔBIC may be more appropriate (Reichardt Chu et al. 2022, 2024). We tested two ΔBIC thresholds: 20, 500. Using a threshold of 20, we detected $[\text{Fe II}]$ emission in ~ 20 per cent of the spaxels with $[\text{O III}] \lambda 4363$ detections, while using a threshold of 500, we detect $[\text{Fe II}]$ in ~ 13 per cent of spaxels. An example of this is shown in Panel (b) of Fig. 2. For this spaxel, we detect $[\text{Fe II}]$ when using a ΔBIC of 20, but not when using a ΔBIC of 500. From this point on, we will consider a ΔBIC of 20. However, it is worth noting that increasing the ΔBIC does not significantly impact the results. In the subsequent sections, we will discuss how the existence of $[\text{Fe II}] \lambda 4360$ in the vicinity of the $[\text{O III}] \lambda 4363$ emission line introduces an element of uncertainty in our measurements.

3.2 Emission line maps

Our KCWI observations show strong $H\beta$ emission at $>5\sigma$ level across the entire field. The top left panel of Fig. 2 shows a map of the $H\beta$ line flux, with values ranging from ~ 2 to $100 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$. We have masked out a region around (0, 700 pc) where a foreground star is present. We define the galaxy centre by the peak luminosity in the *Spitzer*/*IRAC* $3.6 \mu\text{m}$ band (P.I. Fazio, Programme ID 69), as shown by the + symbol in Fig. 2. *HST*/*ACS* $H\alpha$ images also exist of NGC 1569 (P.I. Aloisi, Programme ID 10885), revealing complex, clumpy structures of ionized emission (see Fig. 1). We observe similar structures in $H\beta$ flux. In particular, we note a peak in $H\beta$ flux roughly 250 pc south-east along the major axis of the disc coincident with an H II region in the $H\alpha$ data; a cavity roughly 200 pc south of the major axis, where SSC B is located; and a bright filament extending to

³<https://github.com/astrodee/threadcount>

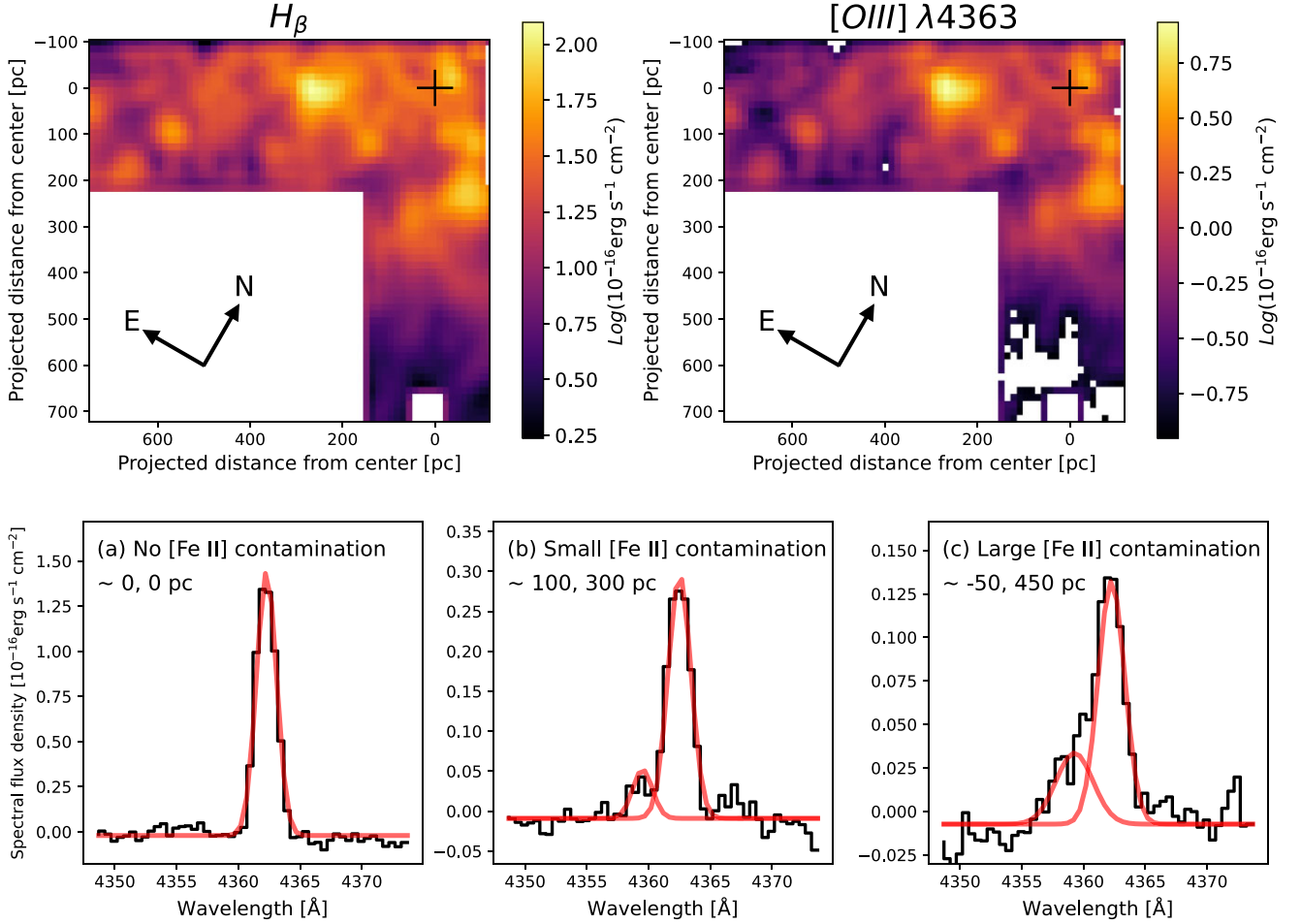


Figure 2. Top row: On the left, emission line flux map of $H\beta$ from KCWI. The x - and y -axes show the position to the galaxy centre, determined from *Spitzer*/IRAC $3.6 \mu\text{m}$ band observations. We mark the centre with a black $+$ symbol. We masked out a $4'' \times 4''$ region around a foreground star at (0, 700 pc). On the right, the emission line flux map of the $[O III] \lambda 4363$ line. The spaxel size is $0.87'' \times 0.87''$ (13×13 pc). SSC B is located near the emission line cavity at (0, 200 pc) in the images. Bottom row: Three examples of the $[O III] \lambda 4363$ emission line. Panel (a) shows a spaxel where we observe no $[Fe II] \lambda 4360$ contamination, panel (b) shows a spaxel with small $[Fe II]$ contamination, and panel (c) shows a spaxel with large $[Fe II]$ contamination. The position in the map for each example is indicated in the top right of each panel. In black we show the data and in red the fit using a ΔBIC of 20.

700 pc south-west along the minor axis of the galaxy. This bright filament is particularly interesting to study outflows because of its association with outflowing gas caused by supernovae. The bright filament shows an $H\beta$ flux that is one order of magnitude higher than its surroundings.

We detect $[O III] \lambda 4363$ at $>3\sigma$ level in 93 per cent of our spaxels, with an upper-limit in the flux of $\sim 0.1 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$. The top right panel of Fig. 2 shows the $[O III] \lambda 4363$ emission line flux. The $[O III]$ flux has a peak of $\sim 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ and decays by 2 orders-of-magnitude towards the minor axis to the edge of the KCWI pointing, ~ 700 pc away from the galaxy centre. The bright $H\beta$ filament can also be observed in $[O III] \lambda 4363$ emission. As stated in subsection 3.1, we observe contamination of $[Fe II] \lambda 4360$ in ~ 20 per cent of spaxels with $[O III] \lambda 4363$ using a ΔBIC of 20. The bottom panel in Fig. 2 shows three examples of $[O III] \lambda 4363$ emission lines with different degrees of $[Fe II] \lambda 4360$ contamination. We have determined the maximum $[Fe II] \lambda 4360$ to $[O III] \lambda 4363$ ratio to be ~ 0.6 and the minimum ~ 0.1 . On average, the $[Fe II]$ flux is 0.2 times the $[O III] \lambda 4363$ flux.

We find very high S/N detections of all strong-lines (e.g. $[O II] \lambda \lambda 3727, 9$ and $[O III] \lambda 5007$) across all fields, all showing similar

structure to $H\beta$ and $[O III] \lambda 4363$ (see Appendix A). We can, therefore, make resolved measurements of T_e and metallicity in both the disc and the filament that is leaving the galaxy to a distance of 700 pc from the mid-plane.

3.3 Separating disc and outflow regions

To determine the metal loading factor, we need to measure the metallicity in the disc and the outflow separately. The galaxy disc has no clear boundary, so it is not straightforward to define where our KCWI field of view is sampling the disc and where it is sampling the outflow. NGC 1569 has been associated with outflows in several studies (e.g. Westmoquette et al. 2007; Johnson et al. 2012), particularly because of the extended $H\alpha$ filaments. Our KCWI observations were planned to sample both the disc and the outflow by placing two pointings parallel to the major axis of the galaxy, on top of the galaxy’s mid-plane (pointing 1 and pointing 2 in Fig. 1) and one on top of a bright $H\alpha$ filament associated with an outflow along the minor axis (pointing 3 in Fig. 1).

With archival *Spitzer*/IRAC observations in the $3.6 \mu\text{m}$ band and Pan-STARRS g-band (Flewelling et al. 2020) observations we

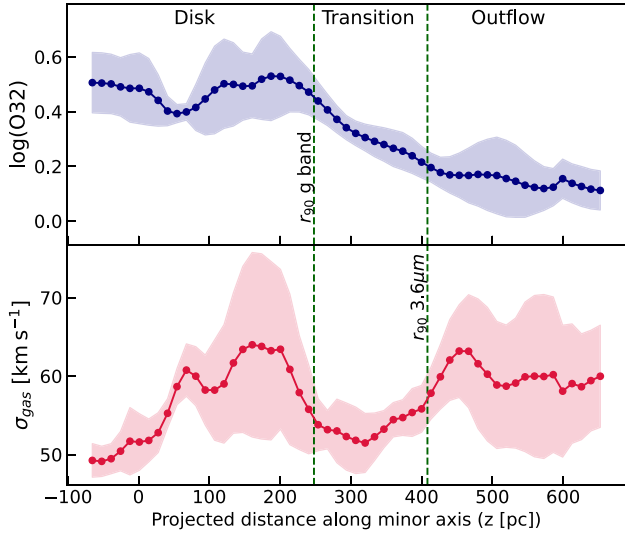


Figure 3. Ionization and velocity dispersion profiles extending above and below the disc mid-plane. Top panel in blue shows $\log(\text{O}32)$ versus z , where z is the distance from the mid-plane of the galaxy in parsecs. Blue points show the mean value in vertical slices parallel to the mid-plane of the galaxy, and the shaded blue area shows the $\pm 1\sigma$ around the mean. The bottom panel in red shows the velocity dispersion from the $[\text{O III}] \lambda 5007$ emission line. Red points show the mean value and the shaded red area shows the $\pm 1\sigma$ around the mean. The green dashed vertical lines at $z \approx 250$ pc and $z \approx 400$ pc, show the distance from the mid-plane at which the integrated flux of PanSTARRS g-band luminosity profile and *Spitzer*/IRAC $3.6 \mu\text{m}$ band luminosity profile reach 90 per cent, respectively. At the top we label the three different regions as defined in subsection 3.3.

determine the vertical extent of the galaxy to define a region where our KCWI observations are sampling the ISM and the outflow. The $3.6\text{-}\mu\text{m}$ band is typically interpreted as a good proxy for total stellar mass in the disc, while the mass-to-light ratio of the g-band will be more affected by younger (< 100 Myr) stars. We measure the surface brightness profile along the minor axis of the galaxy and consider the brightest point to be the mid-plane of the disc. We determine the distance from the mid-plane at which the integrated surface brightness reaches the 50 per cent (r_{50}) and 90 per cent (r_{90}) of the total integrated surface brightness. The results for the IRAC $3.6 \mu\text{m}$ band are: $r_{50, 3.6 \mu\text{m}} \approx 180$ pc and $r_{90, 3.6 \mu\text{m}} \approx 408$ pc. The results for the Pan-STARRS g-band are: $r_{50, g} \approx 86$ pc and $r_{90, g} \approx 247$ pc. This shows that the young stars are distributed more compactly than the older stars.

We explore physical properties of the gas to identify changes that indicate where the line of sight is dominated by the ISM versus the outflow. Using our $[\text{O III}] \lambda 5007$ and $[\text{O II}] \lambda \lambda 3727, 3729$ emission line maps (see Section A) we construct an $O_{32} = [\text{O III}] / [\text{O II}]$ map as a proxy for ionization parameter. We also determine the gas velocity dispersion (σ_{gas}) from the width of the $[\text{O III}] \lambda 5007$ emission line, since it is the line with the highest S/N. The instrumental dispersion of our data is $\sim 45 \text{ km s}^{-1}$. The top panel of Fig. 3 shows the O_{32} profile where z is the distance to the mid-plane of the disc, as defined by the galaxy centre. The $z = 0$ point was defined as the highest brightness in IRAC $3.6 \mu\text{m}$ observations. The blue points and line show the mean value in slices, parallel to the galaxy mid-plane, of our maps and the shaded area shows the 1σ dispersion. At the bottom panel of Fig. 3, we show the velocity dispersion as a function of distance from the mid-plane. The green vertical dashed lines show $r_{90, 3.6 \mu\text{m}}$ and $r_{90, g}$.

The O_{32} profile in Fig. 3 shows that high-ionization gas is coincident with the young stars ($z < r_{90, g} = 250$ pc). This is expected because H II regions are located near the galaxy centre, causing a higher ionization. The velocity dispersion profile shows a peak at $z \approx 180$ pc where SSC B is located, which coincides with a local minimum in ionization. For z between $r_{90, g}$ and $r_{90, 3.6 \mu\text{m}}$ we observe a smooth decrease in ionization and a dip in σ_{gas} . The decrease in ionization is expected because of the larger distance to ionization sources. For distances larger than $r_{90, 3.6 \mu\text{m}}$ we observe an almost flat O_{32} profile, which is an indication that we are sampling far enough from the disc that stars in the disc are not ionizing the gas. If we do not take into account the maximum due to SSC B at 180 pc we observe the highest σ_{gas} in this region. We expect high-velocity dispersion in outflows.

Motivated by the difference in the physical properties that we observe, we define three different zones (1) The high-ionization zone at $z \leq 250$ pc is dominated by young stars and subsequently ionized ISM; (2) the decreasing-ionization zone at $250 \text{ pc} < z < 400$ pc has a mix of young and old stars, resulting in a smoothly decreasing O_{32} and dip in velocity dispersion; and (3) the flat ionization zone at $z > 400$ pc has a much lower surface density of stellar emission (as indicated by the KCWI continuum), producing a flattened low level of O_{32} and high-velocity dispersion driven by outflows. We refer to these regions as ‘Disc dominated’, ‘Transition’, and ‘Outflow dominated’, respectively.

4 MEASUREMENT OF ELECTRON TEMPERATURE AND METALLICITY

With the detection of the strong emission lines plus the detection of $[\text{O III}] \lambda 4363$ in both the disc and the outflow, we can measure the direct-method oxygen abundance or metallicity. We measure the total O/H abundance by measuring the ionic oxygen abundances in two ionization zones, O^+ and O^{++} (assuming the contribution of higher ionization levels is negligible), and adding them together. To determine the O^{++}/H^+ abundance, we use the $[\text{O III}] \lambda 5007/\text{H}\beta$ flux ratio with $T_e([\text{O III}])$ calculated from the electron temperature-sensitive line ratio of $[\text{O III}] \lambda 4363/\lambda 5007$. T_e has a dependence on electron density (n_e) but for our environment we can assume a low $n_e \approx 10^2 \text{ cm}^{-3}$, where T_e is insensitive to n_e (Izotov et al. 2006; Osterbrock & Ferland 2006). We use the `getTemDen` function in `PyNeB` (Luridiana, Morisset & Shaw 2015), with the default atomic data and assumed density, to determine $T_e([\text{O III}])$.

For the O^+ abundance, we use the $[\text{O II}] \lambda 3727/\text{H}\beta$ flux ratio with the $[\text{O II}]$ temperature. Our observations do not cover any low-ionization temperature-sensitive emission lines. We therefore assume a simple positive correlation from Campbell, Terlevich & Melnick (1986).

$$T_e([\text{O II}]) = 0.7 \times T_e([\text{O III}]) + 3000. \quad (2)$$

We measure a mean $T_e([\text{O III}])$ value of 11 408 K with a standard deviation of 515 K in our entire field of view and a mean $T_e([\text{O II}])$ of 10 986 K with standard deviation of 360 K. We note that this correlation is based on observations of H II regions and that there is a large scatter (Rogers et al. 2021). Future work with broader wavelength coverage is needed to determine if this relationship holds in outflows.

We determine the values for O^+ and O^{++} relative abundances over H^+ using the `pyneb` routine `getIonAbundance` which uses as input the flux ratio of a given ion over $\text{H}\beta$. We use $[\text{O III}] \lambda 5007$ and $[\text{O II}] \lambda \lambda 3227, 9$ and the T_e . We measure a median metallicity of 12

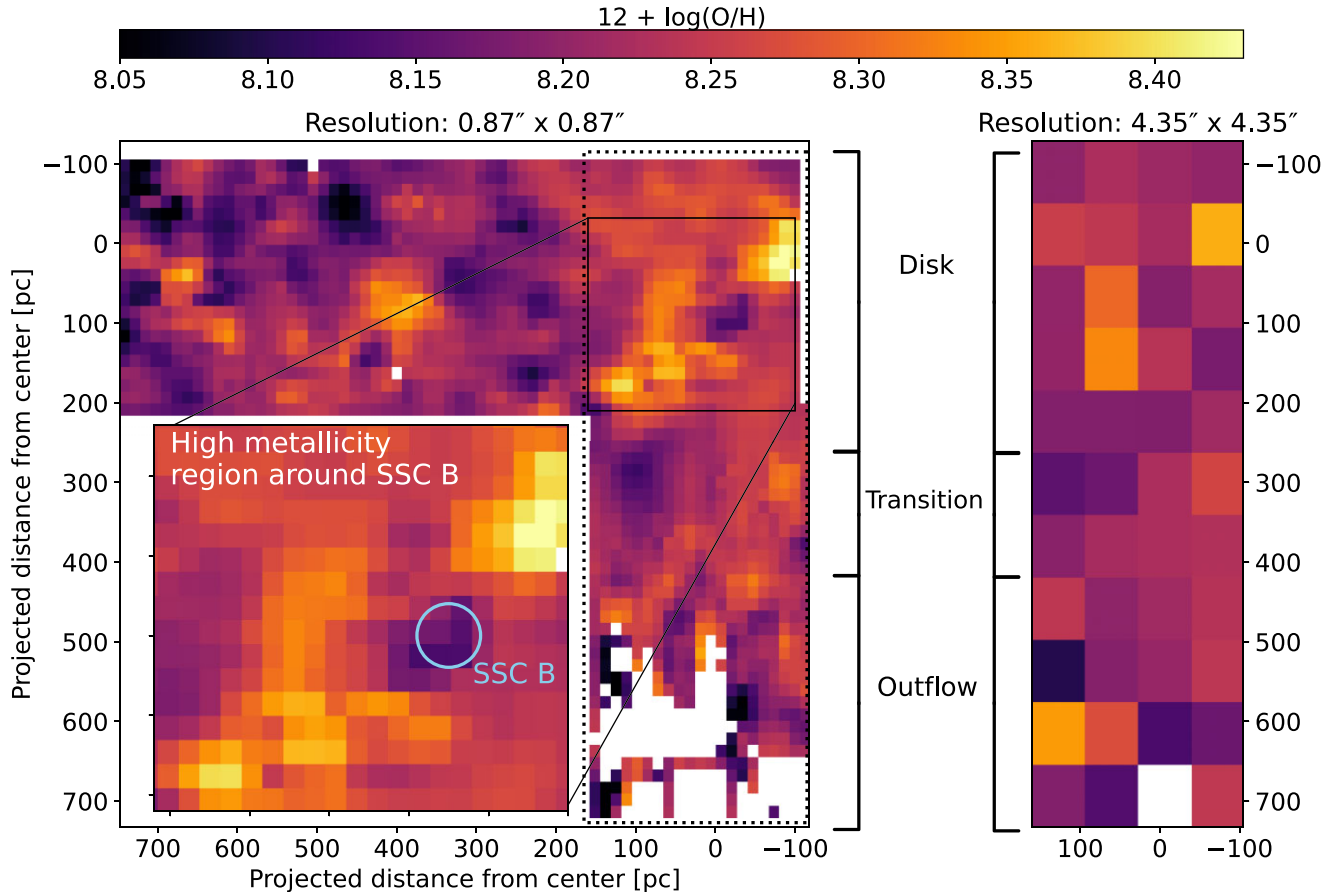


Figure 4. Direct-method metallicity map in $12 + \log(\text{O}/\text{H})$ units. On the left, we show our entire field of view with a spaxel size of $0.87'' \times 0.87''$. In the lower left corner, we show a zoom in of a $17'' \times 15''$ (260×230 pc) region around SSC B. On the right, we show a map of the metallicity, measured from binned data, in the region marked with a black dotted line in the full resolution map. The spaxel size in the binned map is $4.35'' \times 4.35''$. We labelled the disc, transition, and outflow regions according to the definition from subsection 3.3.

$+ \log(\text{O}/\text{H}) = 8.22$ in our entire field of view with standard deviation of 0.14.

The left panel of Fig. 4 shows the $12 + \log(\text{O}/\text{H})$ map for our KCWI field. We observe some metallicity fluctuation in the disc. In particular, we observe higher metallicity around SSC B. We show a zoom in on this particular region in Fig. 4. The right panel shows the $12 + \log(\text{O}/\text{H})$ map from the $4.35'' \times 4.35''$ spatially binned data in the region marked by a dotted black line on the left map. The binned data allows us to get a higher SNR on the $[\text{O III}] \lambda 4363$ emission line at large distances from the mid-plane. In the further sections, we will discuss how the SNR affects metallicity measurements and the metallicity fluctuations we observe in the disc and the outflow.

The presence of $[\text{Fe II}] \lambda 4360$ in some spaxels adds a source of uncertainty to the $[\text{O III}] \lambda 4363$ flux, which can affect our metallicity measurements. The lowest $[\text{Fe II}] \lambda 4360$ to $[\text{O III}] \lambda 4363$ ratio we determine is ~ 0.1 . We might be missing some fainter $[\text{Fe II}]$ emission. If we add 10 per cent of the $[\text{O III}] \lambda 4363$ flux to itself when computing the metallicity, the median metallicity value changes from 8.22 to 8.17. Thus fainter $[\text{Fe II}]$ emission introduces an uncertainty of up to ~ 0.05 to our metallicity measurements. On the other hand, the highest $[\text{Fe II}] \lambda 4360$ to $[\text{O III}] \lambda 4363$ ratio we determine is ~ 0.6 . If we add this per cent to the $[\text{O III}]$ flux when calculating the metallicities we measure a metallicity of 8.00. With lower spectral resolution data, the $[\text{Fe II}]$ might get completely blended with the $[\text{O II}]$ lines, resulting in an under estimation of the metallicity by up to 0.22.

5 ELECTRON TEMPERATURE DISTRIBUTION IN THE DISC

Here we consider the spaxel-to-spaxel variation of T_e , and thus metallicity, in the disc of NGC 1569. We will consider the outflow in a subsequent section. Our data allows us to study the fluctuations of T_e in the ISM on ~ 15 pc scales and compare them to the global measurement. Differences in emission of $[\text{O III}] \lambda 4363$ and $\lambda 5007$ may arise in global measurements (Cameron, Katz & Rey 2023). Moreover, distinct physical regions may impact a global T_e . Our analysis is useful to understand the distribution of metallicity within the disc, and also systematic uncertainties associated with using the direct method to measure metallicity in lower-resolution data (as described in Cameron et al. 2023).

Fig. 5 in grey shows the electron temperature distribution of spaxels in the $0.87'' \times 0.87''$ data in the galaxy disc, normalized by the peak of the distribution. In this section, we only consider gas below the ‘disc’ region as defined in subsection 3.3. The sample has a mean T_e value of ~ 11420 K with a standard deviation of ~ 483 K. We measured the global T_e of the disc from the summed spectra of all spaxels in the disc. We obtained a value of ~ 11409 K. The global measurement for T_e is consistent with our sample’s mean value of all spaxels in the ISM. This implies that T_e fluctuations in scales of around ~ 15 pc do not affect the global measurements of metallicities using the direct method. We note that our observations

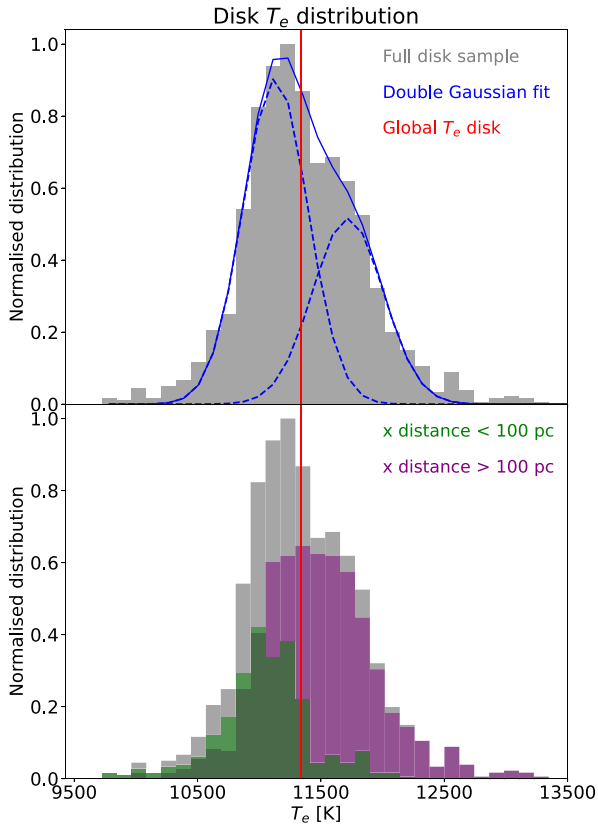


Figure 5. Top panel: The grey histogram shows the distribution of T_e for all spaxels in the $0.87'' \times 0.87''$ data in the disc, normalized by the peak of the distribution. We fitted a double Gaussian to the distribution. The blue lines show the best fit. The red vertical line shows the global T_e value, measured from the ratio of the sum of the [O III] $\lambda 4363$ flux to the sum of the [O III] $\lambda 5007$ flux of all spaxels in the disc. Bottom panel: Same as top panel, in grey we show the normalized distribution of T_e for all spaxels in the disc in the full resolution data. The green histogram shows the distribution for spaxels within ± 100 pc of the galaxy centre. In purple, we show the histogram for spaxels further than 100 pc from the galaxy centre.

do not cover the entire disc. Wider field observations may still generate a discrepancy.

We do however observe an asymmetric profile in Fig. 5. There is a feature at ~ 12000 K, which may indicate a secondary component to the distribution of T_e in NGC 1569. We, therefore, tested this by fitting a double Gaussian model to the distribution, and compare this to a single Gaussian fit to the entire distribution. We use a BIC comparison of the models, and find $\Delta\text{BIC} \sim 2200$. The double Gaussian model is, therefore, strongly favored.

The top panel of Fig. 5 shows the best fit for the distribution of T_e values in the ISM. The two Gaussian components have centroid values of 11 154 K and 11 750 K. In the bottom panel of Fig. 5, we show that this multicomponent behaviour may be recovered by the position within the galaxy. In grey we show again the full distribution in the ISM, but now we also show two histograms based on location within NGC 1569. The green histogram represents spaxels in the ISM that are within ± 100 pc of the galaxy centre. In purple we show the distribution of spaxels in the ISM that are further than 100 pc from the galaxy centre. Those spaxels in the galaxy centre have a median T_e value of 11 103 K, while those at larger distance have median T_e of 11 507 K. This implies that gas at larger distances from the centre

of the galaxy, in the disc zone, tend to have higher T_e values or lower metallicities.

While metal-poor gas at larger distances is often explained by accretion (e.g. Bresolin, Kennicutt & Ryan-Weber 2012; Cameron et al. 2021), the centre of NGC 1569 has multiple structures that may impact the local metal content. We note that signatures of accretion have been observed in NGC 1569 in atomic hydrogen (Mühle et al. 2005). The H I accretion is, however, at significantly larger distance. We will therefore consider if the bright SSC in NGC 1569 is driving these local changes in T_e .

In Fig. 4, SSC B is located at the position [0, 150 pc]. At the bottom left of the plot, we show a zoom in to the region around SSC B. In and around SSC B, we observe a complex metallicity substructure. In those spaxels corresponding to the location of the cluster, we observe a low metallicity. Immediately outside SSC-B, but less than a distance of ± 200 pc we identify two regions with elevated metallicity compared to both the disc and outflow. The first is located roughly south of the SSC, the second one is located to the north of SSC B. From the emission line maps (Fig. 2) and the *HST* image, we observe that the region surrounding SSC B has low flux. This region of high metallicity also corresponds to a region of low ionization, which can be observed in the dip at $z \approx 100$ pc in the $\log(\text{O}32)$ profile (Fig. 3). The lower value of O32 could happen if the [O III] emission was truly due to lower mass density, and thus generating less collisional excitation. Moreover, inspection of H I maps in Johnson (2013) for the same region likewise show a decrease in H I flux. Previous authors argue that supernovae from SSC B produces a superbubble (Westmoquette et al. 2007). The lack of gas and metal enrichment seems consistent with this picture.

From the [O II] $\lambda\lambda 3726$, 9 doublet we measure a median electron density (n_e) of the gas in the ISM of 42 cm^{-3} . Our [O II] $\lambda 3729/\lambda 3726$ line ratios are sufficiently low to consider this n_e near to an upper-limit. The high-metallicity region around SSC B, shown in the zoom-in panel in Fig. 4, has on average a higher n_e . The southern region has a particularly high n_e of $\sim 1300 \text{ cm}^{-3}$, 30 times higher than the mean ISM value. This region has a median $T_e([\text{O} iii])$ value of ~ 10870 K, lower than the ISM median value of 11 430 K. A map of the measured T_e and n_e is shown in Appendix Fig. B1. The ionized gas radiation pressure ($P_{\text{H II}}$) is proportional to the product of T_e and n_e . The mean value for $P_{\text{H II}}/k_B$ in the southern high-metallicity region is $2.2 \times 10^7 (\text{cm}^{-3} \text{ K})$. The median value of $P_{\text{H II}}/k_B$ in the disc is $9.7 \times 10^5 (\text{cm}^{-3} \text{ K})$. The median $P_{\text{H II}}$ in the disc is consistent with values for H II regions in NGC 300 (McLeod et al. 2021). The value in the southern high-metallicity region is ~ 1.5 orders of magnitude higher than their values.

NGC 1569 had a starburst phase 10–20 Myrs ago (Israel 1988; Hunter et al. 2000) where SSC B was formed (Hunter et al. 2000) with a mass of $2.3 \times 10^5 M_\odot$ (Gilbert & Graham 2002). This cluster probably produced hundreds of supernovae that resulted in the superbubble we observe (Sánchez-Cruces et al. 2015). The metal-rich gas surrounding the SSC could be expelled directly from the high star formation in SSC B into the surrounding ISM. A simple explanation is that the gas surrounding the SSC B more heavily favors SNe ejecta, rather than the pre-existing ISM, which allows it to be more metal rich.

The physical properties measured around SSC B could be used to identify starburst (or post-starburst) regions in other galaxies, which may indicate areas in which feedback has disrupted star formation and possibly are the sites of recently disrupted molecular clouds. We list the properties of this starburst region in NGC 1569 in comparison to the ISM of the galaxy. We note that in other galaxies the exact

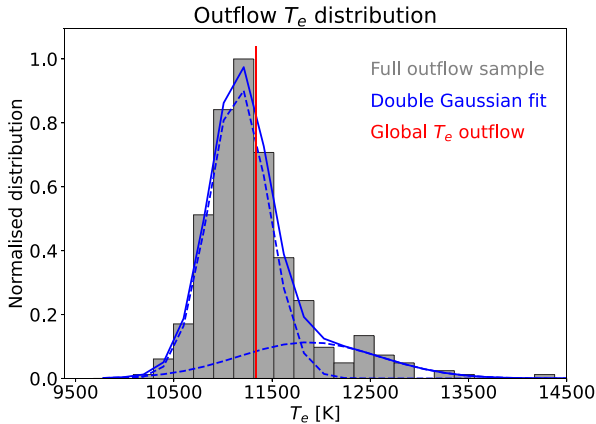


Figure 6. T_e distribution of spaxels in the outflow. Grey histogram shows the distribution of T_e in the $0.87'' \times 0.87''$ data, normalized by the peak of the distribution. In blue, we show a double Gaussian fit to the distribution. The red vertical line shows the global T_e measured from the sum of the spectra of all spaxels in the outflow.

values may change, nevertheless these may provide guidance. The properties of the region include

- (i) high electron density is among the most distinct differences. In this region, n_e reaches values over 10^3 cm^{-3} , while being near to the low density limit for [O II] in the rest of the disc.
- (ii) A decrease in surface brightness of Balmer lines, with respect to the surrounding galaxy, by a factor of 5–10 \times .
- (iii) Lower electron temperature (high metallicity) than the disc. In NGC 1569 this is of order $\Delta T_e \sim 1000 \text{ K}$.
- (iv) Lower ionization in the cavity. In NGC 1569 this is of order a factor of 2–3 \times higher O32 in the disc. We note that NGC 1569 is a higher ionization system. The exact difference may vary.

6 OUTFLOW ENRICHMENT

As we have shown in Fig. 4, we measure the metallicity gradient along the minor axis (z) in the image plane, at a distance of $\sim 700 \text{ pc}$ with a resolution of 15 pc . We consider gas in the outflow region to be at $z > 400 \text{ pc}$, as defined in subsection 3.3. We also defined the ‘transition’ region for $250 < z < 400 \text{ pc}$, where the gas is probably a mix of ISM and outflow. We note that there is not a hard boundary at which an outflow begins, as gas would begin flowing outward from the source of the driving mechanism. We compare the results in this section for $z > 400 \text{ pc}$ and $z > 250 \text{ pc}$ and the results do not change substantially. Therefore, in this section, we will include spaxels from the transition region with $z > 250 \text{ pc}$, and when appropriate discuss any changes with z -axis distance from the galaxy.

The grey shaded histogram in Fig. 6 shows the distribution of T_e for spaxels in the outflow, normalized by the peak of the distribution, for the $0.87 \times 0.87 \text{ arcsec}^2$ spaxel data. We observe that the outflow sample shows a strong peak with a median T_e of 11296 K with standard deviation of 630 K . The distribution shows a tail towards large $T_e \sim 12500$ – 14000 K . As for the disc, we fit single and double Gaussian models to the distribution of T_e in the outflow. We found $\Delta \text{BIC} \sim 100$. This suggests that the double Gaussian model is preferred.

We identified all spaxels with $T_e > 12500 \text{ K}$ to have a mean SNR on the [O III] $\lambda 4363$ line of 3.8, while spaxels with $T_e < 12500 \text{ K}$ have a mean SNR of 6.8. Likewise, spaxels with high-electron density are the faintest detections of emission lines in our maps. To investigate

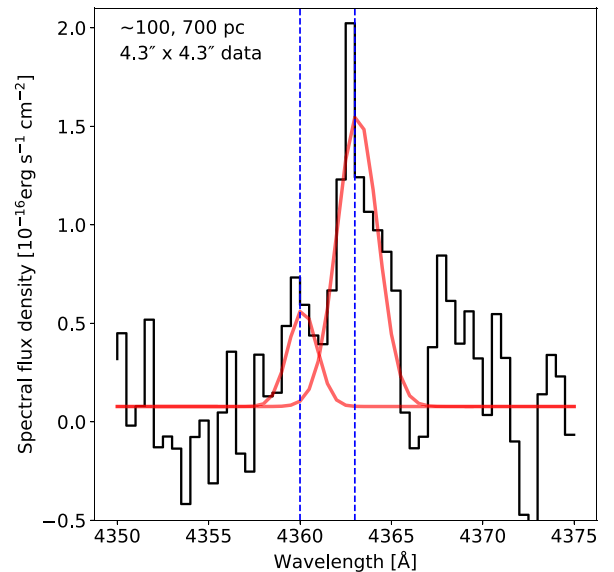


Figure 7. Spectrum of the binned $4.3'' \times 4.3''$ data at the position $\sim 100, 700 \text{ pc}$. The black line shows the data in a wavelength region around the [O III] $\lambda 4363$ emission line. The red line shows the best fit. The second Gaussian at 4360 \AA corresponds to the [Fe II] line. This [Fe II] $\lambda 4360$ feature is not detected in the higher spatial resolution data ($0.87'' \times 0.87''$) in the same region. This results in a higher flux estimation and thus a higher T_e measurement for the higher resolution data.

the impact of low SNR on estimation of T_e , we binned our the data cube to obtain spaxels with size $4.3'' \times 4.3''$. In Fig. 4 we show a metallicity map of the binned data in a region that includes the outflow region and the disc region directly above the outflow. We observe that at the lower spatial resolution we are able to measure the metallicity towards larger distances from the mid-plane. This is because of the increase in SNR on the [O III] $\lambda 4363$ auroral line.

Fig. 7 shows a spectrum of the [O III] $\lambda 4363$ emission line in a binned spaxel at the position $\sim 100, 700 \text{ pc}$. We estimate a SNR of ~ 23 for the [O III] $\lambda 4363$ line. From Fig. 2 we observe that this region in the high resolution map does not show many [O III] $\lambda 4363$ detections. The spaxels where we do find detections have a mean SNR of 3.3. We measure a mean metallicity of $12 + \log(\text{O}/\text{H}) = 8.13$ and a mean T_e of 12834 K for the unbinned data. In the lower resolution map, we observe that this region corresponds to a metallicity of ≈ 8.18 and a T_e of $\approx 12000 \text{ K}$. In their simulations, Cameron et al. (2023) found a systematic bias where the T_e measured from [O III] $\lambda 4363$ /[O III] $\lambda 5007$ overpredicts the true T_e by over $\sim 1000 \text{ K}$ for gas of $T_e = 12000 \text{ K}$. Our offset is high, though not as high.

The red line in Fig. 7 shows the best fit model for the binned data at $\sim 100, 700 \text{ pc}$ using the method described in subsection 3.1. For the spaxel at this position, the BIC method selects a double Gaussian fit in the binned data. The fainter emission bluewards of the [O III] $\lambda 4363$ line corresponds to the [Fe II] $\lambda 4360$ line (Andrews & Martini 2013; Curti et al. 2017). The [Fe II] peak is significantly lower than the peak of [O III] $\lambda 4363$, and is near to the SNR limit in the binned spectrum. In the unbinned spectrum, identifying [Fe II] will likely require high signal-to-noise, which may not be available in the data. If `threadcount` fits a single Gaussian to both the [Fe II] and [O III] features, this would artificially increase the flux attributed to [O III] $\lambda 4363$. This, then, would result in an overestimation of T_e . We therefore caution the reader that the high T_e or low metallicity could be the result of unaccounted for [Fe II] contamination.

The possible contamination of [Fe II] in the outflow motivates us to investigate this further. The [Fe II] $\lambda 4360$ feature is, however, blended with [O III] $\lambda 4363$, which complicates measurement. Curti et al. (2017) showed that the [Fe II] $\lambda 4288$ correlates with the presence of [Fe II] $\lambda 4360$. We estimate [Fe II]/H β in all of our spaxels. We find that in the disc, the median value is 0.005, while in the outflow the ratio is twice as large, [Fe II]/H $\beta \sim 0.009$. We note that this provides an alternate view of enrichment, in which there is stronger [Fe II] in the wind than in the disc. Indeed, Curti et al. (2017) showed that [Fe II] emission is correlated with metallicity. The [Fe II] flux is, however, more difficult to interpret. This may be heavily affected by ionization state. More work is needed to fully interpret these enrichment features. Nevertheless, we take it that this further supports our interpretation that the high T_e tail is likely due to [Fe II] contamination. This should be considered for all T_e measurements that rely on low-SNR measurements of [O III] $\lambda 4363$.

If we assume that the high T_e tail is an artificial effect, then there is not a clear bimodality in T_e in the outflow. This is unlike the disc, which we have discussed shows a variation that may indicate different physical areas of the galaxy. In Fig. 2, we show that in both H β and [O III] emission the outflow contains substructure. Beginning at 300 pc from the galaxy centre, and extending across our field-of-view there is a bright filament in both emission lines. This is likewise seen in the *HST* image (Fig. 1) and has been associated with outflowing gas (Westmoquette, Smith & Gallagher 2008; Johnson 2013). This change in gas substructure does not appear to impact the local metallicity. Fig. 4 shows the metallicity map where the metallicity does not follow the filamentary structure we observe in emission line fluxes. We do not find any significant correlation between the metallicity of the gas and emission line fluxes or ionization in the outflow. This may imply that small scale fluctuations in the T_e of outflows are not a prominent effect.

7 LOW-ELECTRON DENSITY IN THE OUTFLOW OF NGC 1569

In order to estimate the mass of ionized gas in an outflow, a value for the electron density is necessary. As in the disc, our data allows us to estimate the electron density of the outflow of NGC 1569. The [O II] ratio can be used to measure n_e for values of $0.347 < [O II] \lambda 3729 / \lambda 3726 < 1.5$ (Pradhan et al. 2006), where the range is bounded by the so-called low- and high-density limits. Outside this range the ratio reaches asymptotic values.

We detected the [O II] doublet across our entire field-of-view and calculated n_e . Within the measurements errors in emission line fluxes, in the region we defined as the outflow, 43 per cent of the spaxels have values of $[O II] \lambda 3729 / \lambda 3726 > 1.5$. This indicates that n_e is below the low density limit. The lowest n_e we measure, due to measurements uncertainties, is 26 cm^{-3} . The fraction of spaxels in the low density limit increases with distance to the galaxy centre, suggesting that n_e in the outflow decreases with distance from the mid-plane. For spaxels above the low density limit the median n_e is 82 cm^{-3} , this is an upper limit on the outflow electron density.

Typical assumed values for n_e in outflows range from $200\text{--}500 \text{ cm}^{-3}$. These values are derived from large samples of galaxies, mostly high-metallicity ULIRGS and starbursts, with broad emission lines (Förster Schreiber et al. 2019; Fluetsch et al. 2021).

Resolved n_e measurements have been done for a small sample of outflows. Xu et al. (2023) measured n_e for M 82, finding 200 cm^{-3} , which decays as $n_e \propto z^{-1.17}$. Bik et al. (2018) measured n_e from [S II] in the outflow of ESO 0338-IG04, a galaxy with similar metal content to NGC 1569. They found a profile that decays quite steeply

with values $10\text{--}100 \text{ cm}^{-3}$. Our measurement of n_e in the outflow of NGC 1569 is consistent with the low n_e at large distances.

We note the implications for studies that aim to estimate the mass-loading factor of winds, especially those at larger redshift. Our result and that of Bik et al. (2018) are consistent with a scenario in which outflows from lower metallicity galaxies have $n_e \sim 10\text{--}100 \text{ cm}^{-3}$, which is lower than commonly adopted values. The impact of decreasing n_e is to increase the mass loading factor. Recently, Carniani et al. (2023) measured the mass outflow rate for galaxies at redshifts $3 < z < 9$ and found a mass loading factor that is ~ 100 times higher than those in $z = 0$ galaxies. However, it is almost certainly the case that metallicity evolves significantly across this redshift range. More work on the systematics of n_e in outflows for galaxy properties is needed in order to improve estimation from large surveys and accurately inform galaxy evolution modelling.

8 METAL LOADING IN NGC 1569

Fig. 8 shows the electron temperature and metallicity profiles along the minor axis of NGC 1569 for the high resolution ($0.8'' \times 0.8''$ spaxels) and lower resolution data ($4.3'' \times 4.3''$). Within the measurement uncertainty, our observations are consistent with a flat metallicity gradient between the disc and outflow. The median metallicity in the disc region for the high resolution data is 8.21 with a standard deviation of 0.06 and the median metallicity in the outflow region is 8.22 with a standard deviation of 0.06. For the lower resolution data the median metallicity in the disc is 8.19 with a standard deviation of 0.05 and 8.20 in the outflow with standard deviation of 0.06. In both the disc and the outflow, the binned metallicity profile is consistent with the full resolution profile within the scatter of our data. We therefore conclude that the incomplete coverage of the finer spatial resolution does not impact the metallicity gradient along the minor axis of the image.

Garduño et al. (2023) used strong lines to measure the metallicity in NGC 1569. They found a mean metallicity of $12 + \log(\text{O}/\text{H}) = 8.12$. This is similar to our values, considering the typically systematic uncertainties between different methods of measuring metallicity. They also found little variation of metallicity with other properties and distance to the galaxy centre, which is consistent with our flat metallicity profile.

Recently, Vijayan, Krumholz & Winking (2023) carried out box-simulations of supernovae-driven winds which include metallicity effects on the outflow. They included a range of metallicities in the simulation and showed a result with $0.2 Z_\odot$, which is appropriate for comparison to NGC 1569. The shape of the simulated metallicity profile in Vijayan et al. (2023) depends on the gas phase and the initial metallicity of the galaxy. For the warm ionized gas, the profile will be steeper for lower metallicity galaxies. The profile for galaxies with $Z_{\text{ISM}} = 0.2 Z_\odot$ goes from Z_{ISM} in the mid-plane to $\sim 1.1 Z_{\text{ISM}}$ at distances of ~ 1 kpc from the mid-plane. NGC 1569 has a metallicity of $\sim 0.25 Z_\odot$. Considering error bars in our metallicity profile for NGC 1569 it is consistent with the results in Vijayan et al. (2023).

The only other direct-method outflow metallicity profile was observed by Cameron et al. (2021). They measured the metallicity profile along the minor axis of Mrk 1486 up to ~ 1.6 kpc away from the mid-plane. They found that the metallicity at the larger distance was 1.6 times Z_{ISM} . Mrk 1486 has metallicity of $\sim 0.05\text{--}0.1 Z_\odot$. This is likewise consistent with the simulation of Vijayan et al. (2023), as it indicates a steeper profile.

The total mass-loading in the Vijayan et al. (2023) simulation is of order $\dot{M}_{\text{out}}/\text{SFR} \sim 1$. In NGC 1569 McQuinn et al. (2019) estimated

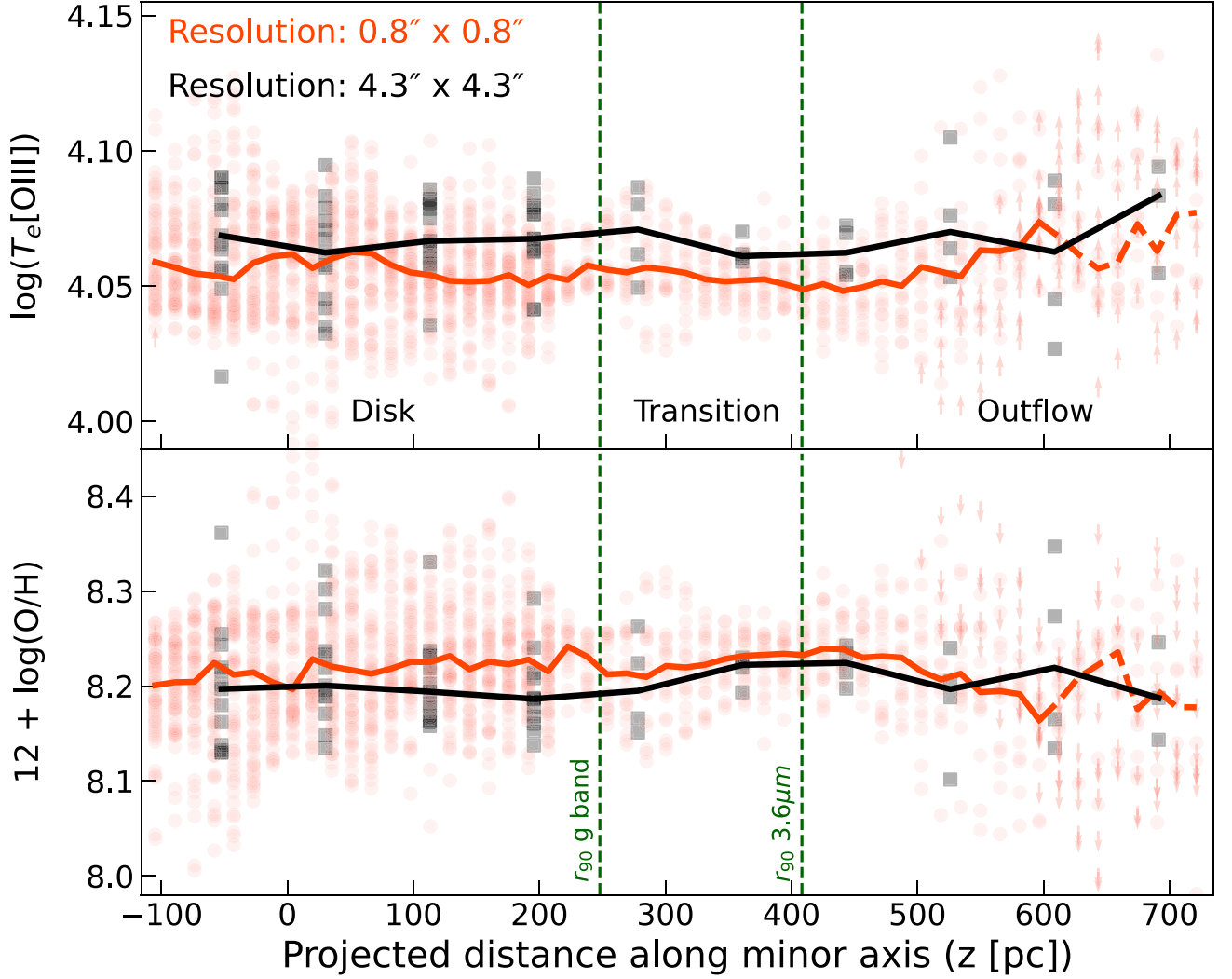


Figure 8. The z -axis profile of T_e and metallicity of NGC 1569. The regions, defined previously, are denoted with vertical dashed lines and labels above the bottom panel. Orange points indicate the individual ~ 15 pc spaxels and orange line indicate upper limits. The solid orange line indicates the median in bins of each row perpendicular to the z -axis, where upper limits are less than 40 per cent of the total measurements. The dotted orange line shows the median in bins where upper limits are more than 40 per cent of the data, in this cases upper limits were ignored in the median calculation. The black squares represent the metallicity profile in binned spaxels with size ~ 65 pc. The metallicity profile in NGC 1569 is consistent with a flat distribution, with very similar metallicity in the disc as in the wind.

the mass-loading of ionized gas to be $\dot{M}_{\text{out}}/\text{SFR} \sim 3$. This does not include the other phases. Results from VLA observations suggest a significant mass component exists with H I gas (Johnson et al. 2012). The total mass loading of NGC 1569 is likely higher. It is not clear how the dependence of mass-loading may, or may not, impact the metallicity profile of the wind. Nevertheless, the current agreement between the very few observations of metal-loading in winds with simulations seems encouraging.

Chisholm et al. (2018) measured the metallicity in the outflow of 7 galaxies using absorption lines. They compared the absorption line wind metallicity to direct-method metallicity measurements of the ISM for each corresponding galaxy. The top panel in Fig. 9 shows $Z_{\text{out}}/Z_{\text{ISM}}$ as a function of stellar mass of the galaxy. In black are the Chisholm et al. (2018) results. They found a steep dependence of increasing $Z_{\text{out}}/Z_{\text{ISM}}$ with decreasing M_* . For galaxies with $M_* < 10^{7.5} M_{\odot}$ outflows are more enriched than the ISM by a factor higher than 10 \times . We note, however, there are only 2 galaxies of this mass

and no galaxies in the Chisholm et al. (2018) sample between $M_* = 10^{7.5} - 10^9 M_{\odot}$.

The magenta symbols in Fig. 9 indicate those measured using T_e -based metallicities in the outflow. Given the significant systematics, the measurement from Cameron et al. (2021) for Mrk 1486 is not inconsistent with that from the absorption lines. For NGC 1569, using the median metallicity in the disc and the median metallicity in the outflow from the full resolution data we get $Z_{\text{out}}/Z_{\text{ISM}} \approx 0.93$. Using the binned data we measure $Z_{\text{out}}/Z_{\text{ISM}} \approx 1.05$. We plotted the value for the binned data as a magenta star in Fig. 9.

The two measurements using direct metallicity method to determine the metallicity in the outflow are within the range of $Z_{\text{out}}/Z_{\text{ISM}}$ for the high-mass galaxies measured with absorption lines. It is not clear if the $Z_{\text{out}}/Z_{\text{ISM}}$ for NGC 1569 is deviating from the trend of low mass galaxies having higher $Z_{\text{out}}/Z_{\text{ISM}}$. NGC 1569 is the third lowest mass galaxy in the figure, and yet has the second lowest

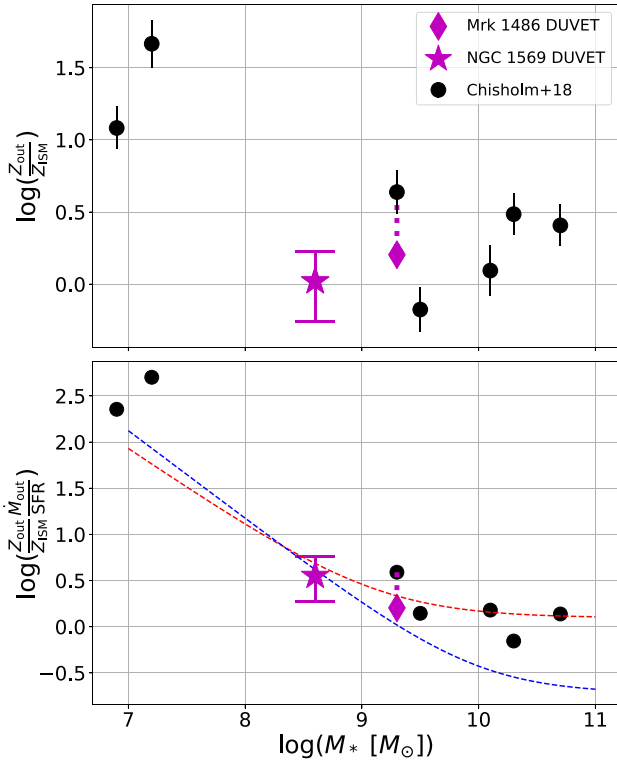


Figure 9. Top panel: $Z_{\text{out}}/Z_{\text{ISM}}$ as a function of M_* . The magenta star shows the result of this work for NGC 1569. The magenta error bars show the two most extreme values depending on what regions we consider as ISM and outflow. The black dots show the results from Chisholm et al. (2018) where they measured Z_{out} from absorption lines and Z_{ISM} using the direct method. The magenta diamond shows the result from Cameron et al. (2021) for Mrk 1486 using the direct method for Z_{out} and Z_{ISM} . The magenta diamond is connected to the Chisholm et al. (2018) measurement for the same galaxy with a magenta dotted line. Bottom panel: $(Z_{\text{out}}/Z_{\text{ISM}}) \times (\dot{M}_{\text{out}}/\text{SFR})$ as a function of M_* . Same colours as the top panel. Red and blue lines show analytical predictions in order to reproduce different MZR in the literature. The red line shows the scaling for the MZR in Tremonti et al. (2004) and the blue line shows the scaling for the MZR in Denicoló, Terlevich & Terlevich (2002).

$Z_{\text{out}}/Z_{\text{ISM}}$. More measurements are needed, in particular for lower mass galaxies.

From the $Z_{\text{out}}/Z_{\text{ISM}}$ measurements we can calculate the metal loading factor (ζ) using equation (1), we show our results in the bottom panel of Fig. 9 as the magenta star. For NGC 1569 we adopt $\frac{\dot{M}_{\text{out}}}{\text{SFR}} \sim 3$ from McQuinn et al. (2019) using $H\alpha$ imaging. The red and blue dotted lines show two models from Peeples & Shankar (2011) that were calibrated to match the MZR observations of Tremonti et al. (2004) and Denicoló et al. (2002). The steep dependence of metal-loading with galaxy mass is necessary to reproduce the MZR.

We show in Fig. 9 that both T_e -based outflow metallicities, the magenta markers, are consistent with the M_* - $(Z_{\text{out}}/Z_{\text{ISM}}) \times (\dot{M}_{\text{out}}/\text{SFR})$ relationship found by Chisholm et al. (2018) using absorption lines. We do, however, urge significant caution for these results. This agreement depends strongly on the mass-loading of the galaxy; in fact the mass loading is a larger fraction of the metal-loading than $Z_{\text{out}}/Z_{\text{ISM}}$. There is a very significant amount of uncertainty in measuring mass-loading of galaxies. Most notably, this mass-loading is only a single phase, which we know to be a smaller fraction of the outflow than cold phase gas. $Z_{\text{out}}/Z_{\text{ISM}}$, which is a

much more robust measurement when using auroral lines than mass-loading, remains low for its mass. More observations are needed, especially at low-stellar mass, to determine if this trend continues.

We observe spatial variations of metallicity in the disc and the outflow regions as shown by the metallicity map, Fig. 4. For example, the region around SSC B shows a particularly high metallicity compared to the disc. To account for this spatial variation, we calculate the minimum $Z_{\text{out}}/Z_{\text{ISM}}$ using the largest metallicity measured in the binned data in the disc and the lowest metallicity measured in the binned data in the outflow. We obtain a minimum $Z_{\text{out}}/Z_{\text{ISM}} = 0.55$. Likewise, we measure the maximum $Z_{\text{out}}/Z_{\text{ISM}}$ using the lowest metallicity measured in the disc and the highest metallicity measured in the outflow. We obtain a maximum $Z_{\text{out}}/Z_{\text{ISM}} = 1.6$. We plot the maximum and minimum $Z_{\text{out}}/Z_{\text{ISM}}$ and $(Z_{\text{out}}/Z_{\text{ISM}}) \times (\dot{M}_{\text{out}}/\text{SFR})$ as error bars to the magenta star in Fig. 9. Even considering the minimum and maximum values, NGC 1569 shows similar metal-loading to high-mass galaxies. We consider that the median values for Z_{ISM} and Z_{out} are a better comparison to Chisholm et al. (2018) measurements because they come closer to a metallicity of the whole disc and the whole outflow.

9 SUMMARY

In this paper we use observations from Keck/KCWI to study the metallicity in the disc and wind of nearby, starbursting dwarf galaxy NGC 1569. Our observations are the second-ever measurement of the metal loading in a galaxy using the direct method metallicity for both the wind and the outflow. The metal loading factor is a necessary input for simulations of galaxy evolution (e.g. Péroux & Howk 2020; Wright et al. 2021), as well as explanations of the MZR and metallicity gradients (Peeples & Shankar 2011; Sharda et al. 2021). We detect the electron temperature sensitive [O III] $\lambda 4363$ emission line across nearly our entire field of view. We measure T_e from the [O III] $\lambda 4363/\lambda 5007$ ratio, then measure the metallicity using the direct method and find $12 + \log(\text{O}/\text{H}) \sim 8.2$ in both disc and outflow.

Our main result is that the metallicity of the wind is comparable to the disc ($Z_{\text{out}}/Z_{\text{ISM}} \sim 1$). We find that direct-method based metal loading factors are consistent with the closed-box derivations of the dependence of metal-loading factors ($\zeta = (Z_{\text{out}}/Z_{\text{ISM}}) \times (\dot{M}_{\text{out}}/\text{SFR})$) on galaxy stellar mass, and are likewise consistent with previous results from absorption line studies (Chisholm et al. 2018). A trend of mass and $Z_{\text{out}}/Z_{\text{ISM}}$ is not clear for the current measurements. As this is a more robust observational quantity to estimate, this may be a concern for the metal-loading of galaxies. A larger sample of galaxies with direct metallicity measurements in the disc and outflow are needed in order to see if a clear trend with mass exists.

The first resolved direct-method measurement of outflow metallicity from Cameron et al. (2021) used 0.7 kpc resolution observations from Keck/KCWI to study the outflow and inflow of Mrk 1486. The observations we present here (Fig. 1) have a spatial resolution of ~ 15 pc, much finer than the previous work from Cameron et al. (2021). We can, therefore, investigate the fluctuation of T_e on scales of ~ 10 – 100 pc, and thus determine how these may impact global measurements. We do not observe any significant metallicity variation in the outflow, which suggests that small T_e fluctuations in the outflow are not a prominent effect.

We show that the sensitivity of the [O III] $\lambda 4363$ line must be taken into consideration when using it to estimate T_e . The reason for this is, as has been shown by Curti et al. (2017), [Fe II] $\lambda 4360$ emission can contaminate the [O III]. At low SNR this may not be easily identified. Very little is known about [Fe II] $\lambda 4360$. We find that even though

our emission line SNR is above $\text{SNR} \sim 5\text{--}10$, spatially binning the data reveals the presence of [Fe II] $\lambda 4360$. The systematic bias of not including [Fe II] $\lambda 4360$ in a fit is to increase the flux attributed to [O III] $\lambda 4363$, and thus increase the estimated T_e . We therefore re-estimate T_e in spatially binned spectra, which can identify [Fe II]. We find that this has the impact of further flattening the z-axis metallicity gradient in the outflow.

We observe a consistent value between the median T_e in high resolution and global T_e measured from the summed spectra. This implies that at a 13 pc resolution, fluctuations in T_e do not affect the global measurements. We note however that our observations do not cover the entire galaxy of NGC 1569. While Cameron et al. (2021) found a significant increase in T_e at extreme ends of the major axis in Mrk 1486, for NGC 1569 we are not able to test if this is impacted by temperature fluctuations. Moreover, fluctuations in T_e may be more important at small scales (Peimbert 2019); we cannot test this with our data.

We do observe local differences in T_e , especially in a region around SSC-B. We find that along with a much lower T_e , the region likewise shows significantly increased electron density ($n_e > 1000 \text{ cm}^{-3}$). We can therefore use the differences in T_e and n_e to derive a local pressure of ionized gas. We find $P_{\text{HII}}/k_b \sim 10^7 \text{ cm}^{-3} \text{ K}$, which is of order $50\times$ larger than the typical pressure of H II regions at similar metallicity (McLeod et al. 2021). We also find decreased surface brightness of H β and H γ and lower ionization. The region, therefore, has a lower mass surface density and is very efficient at cooling. Larsen et al. (2008) derived an age of $\sim 15\text{--}25$ Myr, and Mayya et al. (2020) showed a similar finding with the absence of current Wolf–Rayet stars in the cluster. The implication is that this SSC is no longer experiencing a starburst, and is sufficiently old such that supernovae and early radiative feedback have already destroyed the star forming molecular clouds (see the review Krumholz, McKee & Bland-Hawthorn 2019). The high pressure, high metallicity environment is consistent with a region carved out by supernova ejecta. We propose the properties of the gas around SSC-B as a possible means of identifying similar regions in other galaxies.

We have presented a comprehensive analysis of direct method observations of metal enrichment in the disc and outflow of NGC 1569. Our work is a significant step forward, as it doubles the number of observations that map the metallicity of gas in outflows. It is, however, insufficient. More observations are needed to determine the nature and validity of metal-loading and mass correlations, like we show in Fig. 9.

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DATA AVAILABILITY

All raw data files are accessible in the Keck Observatory Archive⁴. The data underlying this article will be shared on reasonable request to the PI, Deanne Fisher at dfisher@swin.edu.au

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⁴<https://www2.keck.hawaii.edu/koa/public/koa.php>

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APPENDIX A: EMISSION LINE MAPS

With our Keck/KCWI observations we detect common strong emission lines at the $>5\sigma$ level in our entire field of view. Fig. A1 shows the flux map for the [O III] $\lambda 5007$ emission line and the total flux map of the [O II] $\lambda 3727$, 9 doublet. These lines are useful to determine the O32 ratio, which can be used to trace the ionization of the gas. Fig. 3 shows the O32 profile along the minor axis of the galaxy, which was determined from the maps shown in Fig. A1. It can be seen from both the maps and the profile that the O32 ratio decreases with increasing distance along the minor axis.

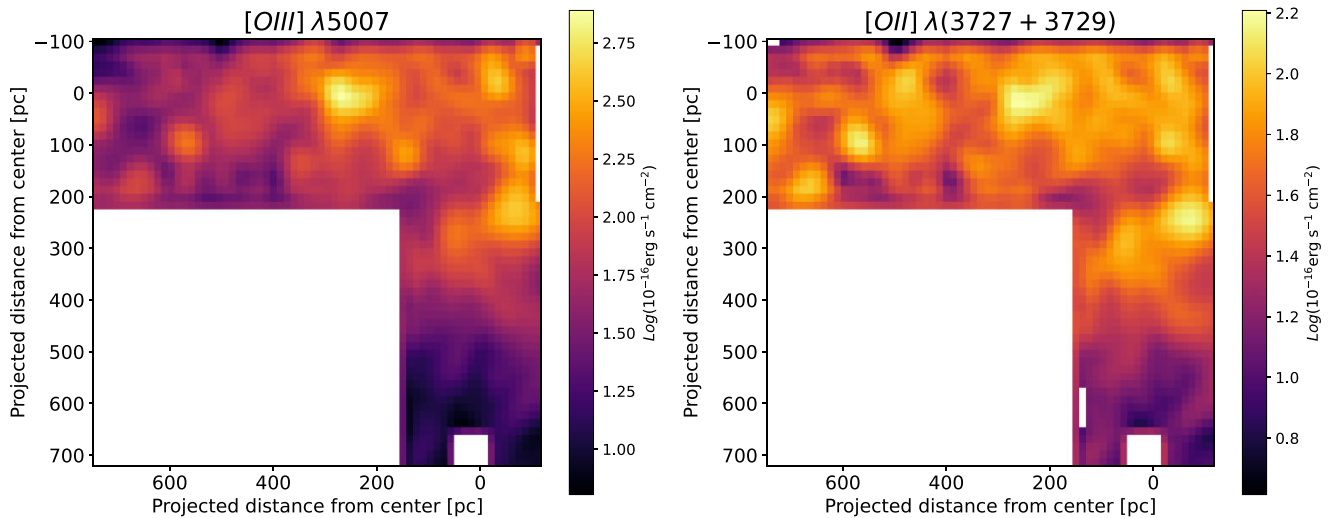


Figure A1. Left panel: Emission line flux map of [O III] $\lambda 5007$ from KCWI. Right panel: Emission line flux map of [O II] $\lambda 3726$ + [O II] $\lambda 3729$ from KCWI. We masked out a $4'' \times 4''$ region around a foreground star at the position $\sim(0, 700)$ pc. SSC B is located near the emission line cavity at $(0, 200)$ pc in the images.

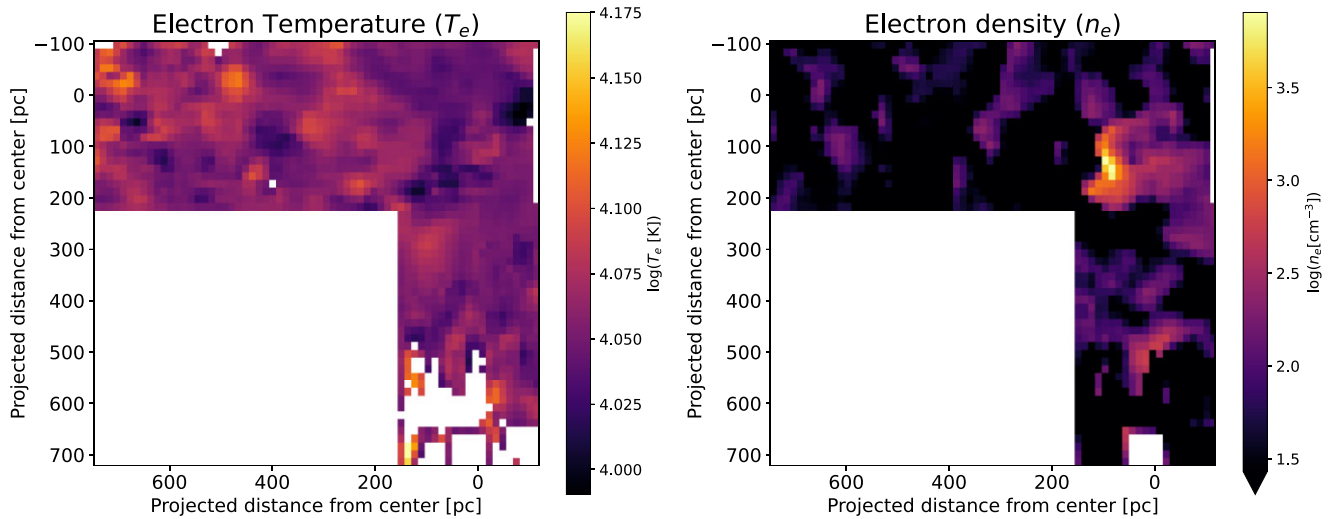


Figure B1. Left panel: Electron temperature map in Kelvins, measured from the $[\text{O III}] \lambda 4363/\lambda 5007$ ratio. Right panel: Electron density map, measured from the $[\text{O II}] \lambda 3729/\lambda 3726$ ratio. Black spaxels show positions at which the $\lambda 3729/\lambda 3726$ ratio reaches the low density limit.

APPENDIX B: ELECTRON TEMPERATURE AND ELECTRON DENSITY MAPS

We measure the electron temperature of the gas from the $[\text{O III}] \lambda 4363/\lambda 5007$ ratio. Fig. B1 shows the T_e map. T_e is inversely proportional to the metallicity, shown in Fig. 4. From the $[\text{O II}] \lambda 3729/\lambda 3726$ we can measure the electron density. Fig. B1 show our measured electron density map. This ratio can be used to measure

n_e for values of $0.347 < [\text{O II}] \lambda 3729/\lambda 3726 < 1.5$. In Fig. B1 we plotted in grey all spaxels for which the ratio, within its errors, is outside of the range. The lowest value of n_e that we measure is $\sim 26 \text{ cm}^{-3}$.

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