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GA-NIFS: an extremely nitrogen-loud and chemically stratified galaxy at $z \sim 5.55$

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ABSTRACT

We report the chemical abundance pattern of GS_3073, a galaxy hosting an overmassive active black hole at $z = 5.55$, by leveraging observations from JWST/NIRSpec and Very Large Telescope/VISible Multi-Object Spectrograph. Based on the rest-frame ultraviolet (UV) emission lines, which trace high-density ($\sim 10^5 \text{ cm}^{-3}$) and highly ionized gas, we derive $\log(N/O) = 0.42_{-0.10}^{+0.13}$. At an estimated metallicity of $0.2 Z_{\odot}$, this is the most extreme nitrogen-rich object found by JWST thus far. In comparison, the relative carbon abundance derived is $\log(C/O) = -0.38_{-0.11}^{+0.13}$, which is not significantly higher than those in local galaxies and stars with similar metallicities. We also found potential detection of [Fe VII] $\lambda 6087$ and [Fe XIV] $\lambda 5303$, both blended with [Ca V]. We inferred a range of Fe abundances compatible with those in local stars and galaxies. Overall, the chemical abundance pattern of GS_3073 is compatible with enrichment by supermassive stars with $M_{*} \gtrsim 1000 M_{\odot}$, asymptotic giant branch stars, or Wolf–Rayet stars. Interestingly, when using optical emission lines that trace lower density ($\sim 10^3 \text{ cm}^{-3}$) and lower ionization gas, we found a sub-solar N/O ratio, consistent with local galaxies at the same metallicity. We interpret the difference in N/O derived from UV lines and optical lines as evidence for a stratified system, where the inner and denser region is both more chemically enriched and more ionized. Our results suggest that nitrogen loudness in high- z galaxies might be confined to the central, dense, and highly ionized regions of the galaxies, while the bulk of the galaxies evolves more normally.

Key words: galaxies: abundances – galaxies: active – galaxies: evolution – galaxies: high-redshift.

1 INTRODUCTION

The chemical abundances of galaxies are imprints of their past evolution (Davé, Finlator & Oppenheimer 2011; Lilly et al. 2013). Observational studies of the chemical abundances of galaxies in the local Universe have found tight correlations between the relative abundances of different elements. The scaling relations between elemental abundances strongly indicate a common chemical evolution pathway in typical galaxies (cf., Maiolino & Mannucci 2019, and references therein). Among the established scaling relations between different elemental abundances, one of the most widely studied is the relation between the oxygen-to-hydrogen abundance, O/H, and the nitrogen-to-oxygen abundance, N/O. Previous observations have

shown a correlation between O/H and N/O in local H II regions and in the interstellar medium (ISM) of star-forming (SF) galaxies (e.g. Vila-Costas & Edmunds 1993; van Zee et al. 1998; Pilyugin, Grebel & Mattsson 2012; Andrews & Martini 2013; Berg et al. 2016, 2019, 2020; Belfiore et al. 2017; Nicholls et al. 2017; Hayden-Pawson et al. 2022). At low oxygen abundances, or ‘metallicities’, the abundance ratio of N/O asymptotically approaches a constant value. In contrast, in the intermediate to high-metallicity regime, N/O roughly scales quadratically with O/H (Nicholls et al. 2017). In theory, this behaviour is a reflection of the different enrichment mechanisms of oxygen and nitrogen. The oxygen in the ISM is promptly enriched by core-collapse supernovae (CCSNe, from massive stars with stellar masses of $M_{*} \gtrsim 8 M_{\odot}$ and short lifetimes). In contrast, the enrichment of nitrogen has another path available through stellar winds during the asymptotic giant branch (AGB) phase of intermediate-mass stars with stellar masses of $2 M_{\odot} < M_{*} < 8 M_{\odot}$.

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Due to the CNO cycle at work in the intermediate-mass stars, the nitrogen production is boosted in the metal-rich stars, leading to the scaling relation between O/H and N/O. Since the enrichment by AGB stars lags behind the enrichment by CCSNe, there is expected to be an intrinsic scatter around the scaling relation (e.g. Andrews & Martini 2013). In addition, the inflow of low-metallicity gas, as well as variations in the star formation efficiency, can also lead to scatter in the N/O versus O/H relation (Vincenzo et al. 2016; Kumari et al. 2018; Schaefer et al. 2020; Luo et al. 2021).

Despite the intrinsic scatter of the N/O versus O/H relation, it is rare to observe galaxies with an N/O deviating from the locally established relation by more than 0.5 dex. One interesting outlier, for example, is a local compact dwarf galaxy Mrk 996, which has a rather high nitrogen abundance of $\log(\text{N/O}) = -0.76$ (or $[\text{N/O}] \equiv \log(\text{N/O}) - \log(\text{N/O})_{\odot} = 0.10$) considering its extremely low metallicity of $12 + \log(\text{O/H}) = 7.15$ (or $[\text{O/H}] = -1.54$; Thuan, Izotov & Lipovetsky 1996; Berg et al. 2016). More recently, by reanalysing the UV emission lines of Mrk 996 with photoionization models, Senchyna et al. (2024) and Isobe et al. (2023) inferred an even higher abundance ratio of $[\text{N/O}] \sim 0.86$. According to James et al. (2009), however, the emission-line spectrum of Mrk 996 has two kinematic components, indicative of two distinct regions with different gas densities and abundance patterns. The low-density region has a density of $n_e = 170 \pm 40 \text{ cm}^{-3}$ and a lower nitrogen abundance of $\log(\text{N/O}) = -1.43 \pm 0.14$. In contrast, the high-density region has a density of $\log(n_e/\text{cm}^{-3}) = 7.25^{+1.25}_{-0.75}$ and a higher nitrogen abundance of $\log(\text{N/O}) = -0.13 \pm 0.28$. The ‘nitrogen-loudness’ of this target potentially comes from the peculiar enrichment from Wolf–Rayet (WR; e.g. Crowther 2007) stars, where the powerful stellar winds enriched with light elements, including nitrogen, boost N/O even though the metallicity is low. Due to the relatively short time-scale of the WR phase, the enhanced N/O would be quickly lowered again by enrichment from CCSNe of massive stars a few Myr after the initial burst of star formation (Limongi & Chieffi 2018; Watanabe et al. 2024). Thus, it is expected that such a peculiar abundance pattern should be rarely encountered in observations. As another example of nitrogen enhanced star-forming system, a young super star cluster with Lyman continuum leakage (LyC) in the gravitationally lensed Sunburst Arc at $z = 2.37$ was recently found to show both a pressure (and density) stratification and a nitrogen abundance stratification (Pascale et al. 2023). According to Pascale et al. (2023), the high-pressure and high-density region in the LyC cluster has an enhanced nitrogen abundance of $\log(\text{N/O}) = -0.21^{+0.10}_{-0.11}$ at a low metallicity of $12 + \log(\text{O/H}) = 8.03 \pm 0.06$.

Interestingly, previous observations have revealed a population of active galactic nuclei (AGNs) potentially having enhanced nitrogen abundances, which are called ‘nitrogen-loud’ AGNs (Baldwin et al. 2003). Nitrogen-loud AGNs are a rare subclass of AGNs (~ 1 per cent in SDSS quasars with $1.6 \lesssim z \lesssim 4$; Bentz & Osmer 2004; Bentz, Hall & Osmer 2004; Jiang, Fan & Vestergaard 2008). The nitrogen loudness refers to the strong rest-frame UV nitrogen lines observed in these AGNs. These AGNs typically show clear broad components in the strong UV nitrogen lines, and the abundance estimations based on the nitrogen lines have suggested significantly supersolar metallicities (e.g. Hamann & Ferland 1992; Baldwin et al. 2003; Dietrich et al. 2003; Nagao, Marconi & Maiolino 2006a). There are a number of long-standing questions about nitrogen-loud AGNs, including whether elements other than nitrogen are also enriched, whether the nitrogen-loudness is only limited to the broad-line regions (BLRs), and so forth (Collin & Zahn 1999; Baldwin et al. 2003; Jiang et al. 2008; Matsuoka et al. 2011, 2017; Wang et al. 2011; Araki et al. 2012; Batra & Baldwin 2014; Villar Martín et al. 2020).

There are also discussions on the potential systematic uncertainties of abundance estimations based on broad emission lines (Batra & Baldwin 2014; Temple et al. 2021). For the enrichment mechanisms of these nitrogen-loud AGNs, depending on the actual abundance pattern and the site of the enrichment, it is possible to have fast enrichment within the small nuclear region (Collin & Zahn 1999; Wang et al. 2011; Cantiello, Jermyn & Lin 2021; Ali-Dib & Lin 2023; Huang, Lin & Shields 2023; Chen & Lin 2024) or wide-spread enrichment during a specific stage of galaxy evolution (Hamann & Ferland 1993; Baldwin et al. 2003). To provide more constraints on the true nature of nitrogen-loud AGNs, it is thus important to probe the chemical abundances of different elements as well as within different ionization zones in AGNs. It is also vital to find evidence of nitrogen enrichment in the nitrogen-loud AGNs at early times.

Based on the local N/O versus O/H relation, one might expect high redshift galaxies to populate the low-metallicity end of the relation. Intriguingly, with the advent of the JWST (Gardner et al. 2023; Rigby et al. 2023), an abundance pattern with enhanced N/O has recently been confirmed in a galaxy, GN-z11, at $z = 10.603$ (Bunker et al. 2023; Cameron et al. 2023). It is noteworthy that the flux ratios between the semiforbidden transitions of N III] as well as the flux ratio between [N IV] and N IV] in the JWST spectrum of GN-z11 indicate a high density (Maiolino et al. 2024b), typical of the BLRs of AGNs (Netzer 1990). Based on flux measurements of UV emission lines in GN-z11, Cameron et al. (2023) inferred a fiducial abundance ratio of $[\text{N/O}] > 0.61$. This puts GN-z11 in the category of nitrogen-loud AGNs previously found at lower redshifts and raises the question about the enrichment site of nitrogen in this galaxy (Cameron et al. 2023; Maiolino et al. 2024b). Thus far, several nitrogen-loud galaxies at redshifts of $z > 6$ have been confirmed spectroscopically by JWST (Bunker et al. 2023; Cameron et al. 2023; Isobe et al. 2023; Senchyna et al. 2024; Castellano et al. 2024; Schaerer et al. 2024; Topping et al. 2024). These nitrogen-loud galaxies are characterized by strong rest-frame UV emission from high ionization species of nitrogen, including N III] λ 1746–1754 and N IV] λ 1483, 1486, with fluxes considerably higher than that of the UV oxygen emission from O III] λ 1661, 1666. The discovery of these sources seems to suggest a higher fraction of nitrogen-loud galaxies in the early Universe. Still, most of the high redshift galaxies currently observed are not bright enough for reliable constraints on the nitrogen abundance (Isobe et al. 2023). To explain the peculiar abundance pattern of these systems, especially given their age, various enrichment mechanisms have been proposed including WR stellar winds with direct-collapse WR stars, winds from very massive stars (VMSS, with $M_* > 100 M_{\odot}$) and supermassive stars (SMSs, with $M_* > 1000 M_{\odot}$), and tidal disruption events (TDEs; Cameron et al. 2023; Charbonnel et al. 2023; Nagele & Umeda 2023; Senchyna et al. 2024; Vink 2023; Kobayashi & Ferrara 2024; Nandal et al. 2024; Watanabe et al. 2024). It remains unclear whether these enrichment mechanisms have any connections with AGN activity.

With JWST observations, we can now explore more details on the abundance pattern of nitrogen-loud galaxies/AGNs in the early Universe. One particular target of interest for exploring the nature of nitrogen loudness in high- z galaxies is GS_3073 (RA: $3^{\text{h}}32^{\text{m}}18.93^{\text{s}}$, Dec.: $-27^{\circ}53'2.96''$) found in the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey/Great Observatories Origins Deep Survey field centered on the Chandra Deep Field South (CANDELS/GOODS-S; Koekemoer et al. 2011). The target was previously observed by ground-based spectroscopy and was confirmed to have a redshift of $z \sim 5.55$ (Vanzella et al. 2010; McLure et al. 2018; Grazian et al. 2020). Based on emission line ratio diagnostics, Grazian et al. (2020) and Barchiesi et al. (2023)

speculated that there is AGN activity in GS_3073. Recent observations taken with JWST/Near InfraRed Spectrograph (NIRSpec) integral field unit (IFU) confirmed it is a Type-1 AGN (specifically type 1.8) showing prominent broad emission lines in the rest-frame optical (Übler et al. 2023). The supermassive black hole (SMBH) in GS_3073 appears ‘overmassive’, with its mass lying above the local black hole mass versus stellar mass relation (Übler et al. 2023). Interestingly, the JWST/NIRSpec PRISM observation of GS_3073 reveals strong nitrogen lines in the rest-frame UV spectrum, which potentially put GS_3073 among the nitrogen-loud Type-1 AGNs observed at the highest redshifts (Übler et al. 2023). At the same time, with the NIRSpec coverage of the rest-frame optical regime of GS_3073, forbidden transitions of [N II] are also detected. Thus, it is possible to explore the nitrogen abundance in different density regimes. In this work, we investigate the chemical abundance pattern of GS_3073, combining ground-based spectroscopic data from the Very Large Telescope/VISible Multi-Object Spectrograph (VLT/VIMOS) and space-based spectroscopic data primarily from the JWST/NIRSpec PRISM.

The layout of the manuscript is as follows. In Section 2, we describe the observational data and data reduction. In Section 3, we describe the method we used to fit the observed spectra of GS_3073. In Section 4, we derive the chemical abundances of GS_3073 based on our emission-line measurements. We discuss the enrichment mechanism as well as the enrichment site in this galaxy in Section 5 and draw our conclusions in Section 6.

Throughout the manuscript, we assume a flat Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_\Lambda = 0.7$, and $\Omega_m = 0.3$. We assume solar abundances provided in Grevesse et al. (2010) (with $12 + \log(\text{O}/\text{H})_\odot = 8.69$, $12 + \log(\text{N}/\text{H})_\odot = 7.83$, and $12 + \log(\text{C}/\text{H})_\odot = 8.43$) unless otherwise specified.

2 OBSERVATIONAL DATA

In this work, we used both space- and ground-based spectra for GS_3073. The space-based spectra were obtained with the IFU of JWST/NIRSpec (Böker et al. 2022, 2023; Jakobsen et al. 2022) and the ground-based spectrum was obtained with VIMOS (Le Fèvre et al. 2003), formerly at VLT. Below we summarize these observations.

2.1 JWST/NIRSpec observation and data processing

The JWST/NIRSpec observations of GS_3073 discussed here are from the GTO Program, Galaxy Assembly with NIRSpec IFS (GANIFS; Program ID 1216; PI: Nora Lützgendorf). The configuration of the observation is detailed in Übler et al. (2023). In brief, two dispersers were used, resulting in IFU cubes with different spectral resolutions. The high-resolution IFU cube was obtained using the G395H grating, and has a total integration time of 5 h. The final G395H spectra have a spectral resolution of $R \sim 1900\text{--}3600$, and covers the spectral range $2.85\text{--}4.85 \mu\text{m}$, which corresponds to $4400\text{--}7400 \text{ \AA}$ in the rest frame of GS_3073. The low-resolution IFU cube was obtained using the PRISM disperser, and has a total integration time of 1.1 h. The final PRISM spectra have a spectral resolution of $R \sim 30\text{--}300$, covering a spectral range of $0.6\text{--}5.3 \mu\text{m}$ in the observed frame and $900\text{--}8100 \text{ \AA}$ in the rest frame of GS_3073.

In this work, we utilize the NIRSpec PRISM observations of GS_3073. Raw data files were downloaded from the Barbara A. Mikulski Archive for Space Telescopes (MAST) and processed with

the JWST Science Calibration pipeline¹ version 1.11.1 under the Calibration Reference Data System (CRDS) context `jwst.1143.pmap`. We made some modifications to the default reduction steps to produce the data cube (see Perna et al. 2023, for details). The final cube was combined using the ‘drizzle’ method. The analysis in this paper is based on the combined cube with a pixel scale of 0.05 arcsec . To subtract the background (which is assumed to be uniform across the IFU field of view), we constructed an inverse-variance weighted average spectrum from the spaxels outside the central $1 \text{ arcsec} \times 1 \text{ arcsec}$ region, where no apparent emission line feature can be found. We then subtracted this average background spectrum from the central spaxels. We tested different background extractions with excluded central areas ranging from $0.6 \text{ arcsec} \times 0.6 \text{ arcsec}$ to $1.4 \text{ arcsec} \times 1.4 \text{ arcsec}$ and the results are essentially the same.

The low spectrum resolution of the PRISM spectrum leads to blending of several important rest-frame UV emission lines, such as Ly α and N V, and [N IV] λ 1483 and N IV] λ 1486. To deblend these lines, we used the publicly available VLT/VIMOS spectrum of GS_3073 that overlaps with the PRISM spectrum in the observational wavelength range of $0.6 \mu\text{m} < \lambda < 1.03 \mu\text{m}$. The VLT/VIMOS spectrum can also provide a consistency check for emission-line fluxes measured from the PRISM spectrum.

2.2 VLT/VIMOS observation

The VLT/VIMOS spectrum, we used was extracted from the observations by the multi-object spectroscopy survey VANDELS, with an integration time of 20 h (ESO program ID 194-A-2003; McLure et al. 2018). This source was assigned to a slit with a width of 1 arcsec (McLure et al. 2018), which gives a nominal spectral resolution of $R \sim 580$. The slit width is larger than the size of GS_3073, which is around $0.15 \text{ arcsec}\text{--}0.30 \text{ arcsec}$ from the GALFIT results of previous observations (Vanzella et al. 2010; van der Wel et al. 2012) as well as from the inspection of the rest-frame UV fluxes from the JWST/NIRSpec PRISM IFU cube (Übler et al. 2023). Despite the compact size of GS_3073, the typical full width at half maximum (FWHM) of the point spread function (PSF) of VANDELS observations is $\sim 0.6 \text{ arcsec}\text{--}1.0 \text{ arcsec}$ (McLure et al. 2018), meaning the actual spectral resolution of the data could vary in a range of $580 \lesssim R \lesssim 970$. We used the 1D spectrum reduced by Grazian et al. (2020) with the reduction pipeline described in Grazian et al. (2018).

The VIMOS spectrum covers a spectral range of $4800\text{--}10300 \text{ \AA}$ in the observed frame and $700\text{--}1600 \text{ \AA}$ in the rest frame of GS_3073. Within this spectral regime, detection of emission lines including O VI] λ 1032, 1038, Ly α , N V] λ 1238, 1242, C III] λ 1334, 1335, and N IV] λ 1483, 1486 was previously reported (Grazian et al. 2020; Barchiesi et al. 2023). We note that previous spectroscopic observations of GS_3073 with the FOCAL Reducer and low dispersion Spectrograph (FOR2) at VLT (Vanzella et al. 2010) and X-Shooter at VLT (Program IDs: 384.A-0886 and 089.A-0679) cover a similar spectral regime. While Ly α and N IV] λ 1483, 1486 are also detected in the FOR2 spectrum and X-Shooter spectrum (Raiter, Fosbury & Teimoorinia 2010; Grazian et al. 2020), the VIMOS spectrum has the highest signal-to-noise ratio (S/N) and is the only one showing the clear detection of all the aforementioned emission lines.

In the next section, we describe the method we adopted to fit the JWST/NIRSpec and VLT/VIMOS spectra and show the fitting results.

¹<https://jwst-pipeline.readthedocs.io/en/stable/jwst/introduction.html>

3 SPECTRAL FITTING

We used the Penalized PiXel-Fitting code (pPXF; Cappellari & Emsellem 2004; Cappellari 2017) to perform spectral fitting.

3.1 JWST/NIRSpec PRISM spectrum

Our main focus is on emission line fluxes. For the JWST/NIRSpec PRISM IFU observations, we extract the central $0.3 \text{ arcsec} \times 0.3 \text{ arcsec}$ (or equivalently $1.8 \text{ kpc} \times 1.8 \text{ kpc}$) to match the fluxes measured from the JWST/NIRSpec high-resolution spectrum in Übler et al. (2023). We used a combination of power-law functions and an analytical function for an optically thin Balmer continuum (Grandi 1982) to fit the rest-frame UV-to-optical continuum simultaneously with emission lines. Specifically, we used three power laws, one has a slope of -2.33 following the Shakura & Sunyaev (1973; SS73) accretion disc, the other two have slopes of -2.66 and 0.5 , respectively. The fitting results are relatively insensitive to the values of the latter two slopes and their role is to account for deviation from the SS73 disc. The Balmer continuum component, on the other hand, is motivated by the clear Balmer jump feature in the rest-frame near UV spectrum of GS.3073. To account for variations in the continuum shape and the effect of dust attenuation, we included 8th-order multiplicative polynomials when fitting the continuum. We also tried 4th-order multiplicative polynomials and our results are unaffected. Since our main focus is on emission-line fluxes, we did not attempt to interpret the physical origin of the continuum based on spectral fitting.

As shown by Übler et al. (2023), the G395H spectrum of GS.3073 reveals several kinematic components in optical emission lines. In the G395H spectrum, there is detection of a broad component in the Balmer lines and optical He I and He II lines with an FWHM of $3370.4 \pm 41.4 \text{ km s}^{-1}$ as well as an outflow component with an FWHM of $1306.7 \pm 23.7 \text{ km s}^{-1}$. In contrast, for forbidden lines in the optical, Übler et al. (2023) only found a narrow component and an outflow component.

We assumed Gaussian profiles for emission lines. During the fit of emission lines, we included two different kinematic components for Balmer lines as well as optical He I and He II lines to represent the narrow components and the broad components. We tied the kinematics of all narrow lines and broad lines, respectively. Since the spectral resolution of the PRISM spectrum ($R \sim 30\text{--}300$) is generally not high enough to separate the two sets of components, we fixed the velocity dispersion of the narrow component to the values measured from the G395H spectrum in Übler et al. (2023) convolved with the nominal resolution of the PRISM spectrum. For the broad component, however, we did not fix its velocity dispersion to the value derived by Übler et al. (2023) in order to account for potential mismatch between the nominal spectral resolution and the actual spectral resolution (Jakobsen et al. 2022; de Graaff et al. 2024). Following the results of Übler et al. (2023), for each line, if there are both narrow and broad components, we set the velocities of the two components the same. For optical forbidden lines, only the narrow components were considered. Finally, we tied the kinematics of all narrow optical lines and those of all broad optical lines, respectively. While Übler et al. (2023) identified an outflow component for optical lines in the G395H spectrum, to avoid overfitting of the low-resolution spectrum, we did not include a third kinematic component. The outflow contribution to the flux as fitted by Übler et al. (2023) is in general small for strong lines and we discuss its potential impact when analysing specific lines. For UV lines, we simply considered a single kinematic component due to the much

lower spectral resolution. This means the UV line fluxes we measured should be the total fluxes including both broad line fluxes and narrow line fluxes. During our analyses later in the manuscript, we discuss the effects of such blending on our results. We tied the kinematics of all UV lines except Ly α due to the complex nature of its intrinsic line profile. While N V, C II, and C IV are also resonant or have a resonant component, the spectral resolution of the PRISM spectrum at their locations are relatively low and insufficient to discern their potentially different kinematics. As a sanity check, we performed a fit where the kinematics of the above lines are set free. The final fluxes we obtained are consistent with our current fitting results within 1σ of the measurement uncertainties.

To account for the spatial covariance of the flux errors, we first calculated the integrated errors assuming all spaxels are independent. We then performed an initial spectral fit assuming the true errors equal to the integrated errors. Next, we rescaled the integrated errors using the standard deviation obtained from the residuals of the initial fit. To do this, we calculated standard deviations within several spectral windows without apparent emission features. We inspected five spectral regions in the spectrum centred around 2400, 3300, 5600, 6300, and 7700 Å in the rest frame, and we tested different widths for the spectral regions.² The standard deviations obtained from these regions are in general 2–3 times larger than the integrated errors and thus we scaled up all integrated errors by a factor of 3 as a conservative estimation. The final flux uncertainty for each emission line was calculated by adding the noise to the original spectrum and refitting. We repeated the above procedure 500 times and took the standard deviation of the flux distribution divided by $\sqrt{2}$ as the final uncertainty (since the effective flux uncertainties have been enlarged by a factor of $\sqrt{2}$ after adding the noise). The uncertainty calculated this way is broadly consistent with the formal error reported by pPXF.

Fig. 1 shows the fitting result of our extracted PRISM spectrum. The continuum model suggests the existence of a Balmer continuum. Meanwhile, the UV continuum appears to feature a few bumps spanning from 2200 Å to 3600 Å. We speculate the existence of Fe II emission in this regime and will present the analyses in a future paper. In the optical, one can see a clear broad component in H α even at the low resolution of the PRISM spectrum. Our fit gives $\text{FWHM}_{\text{H}\alpha} \sim 4.3 \times 10^3 \text{ km s}^{-1}$ for the broad component. This is larger than the value measured by Übler et al. (2023) from the high resolution G395H spectrum, which is $\text{FWHM}_{\text{H}\alpha} = 3370.4 \pm 41.4 \text{ km s}^{-1}$. The difference is likely due to our adoption of a canonical spectral resolution for the PRISM spectrum, which could be different from the actual spectral resolution in observations. Judging from the residuals, the emission lines are overall well-fitted. The bottom panels of Figs 1 and 2 show the zoom-in views around several UV lines and weak optical lines. Specifically, we plotted the zoom-in view around H α on a logarithmic scale to highlight the potential detection of weak coronal lines of Fe.

We summarize the fluxes of emission lines in Table 1. We also list the emission line fluxes measured from the high resolution spectrum by Übler et al. (2023). These fluxes are measured within the central $0.3 \text{ arcsec} \times 0.3 \text{ arcsec}$ region of the G395H IFU cube. For each line, we simply summed all its kinematic components. While the [O III] λ 5007 flux from the PRISM matches that from the G395H grating, other strong lines such as H α , H β , and He I λ 7065 have their PRISM fluxes higher than the G395H fluxes by ~ 20 per cent. We note that the flux differences might come from a mix of effects

²We caution, however, that the spectral regime in the rest-frame UV might be contaminated by Fe II emission.

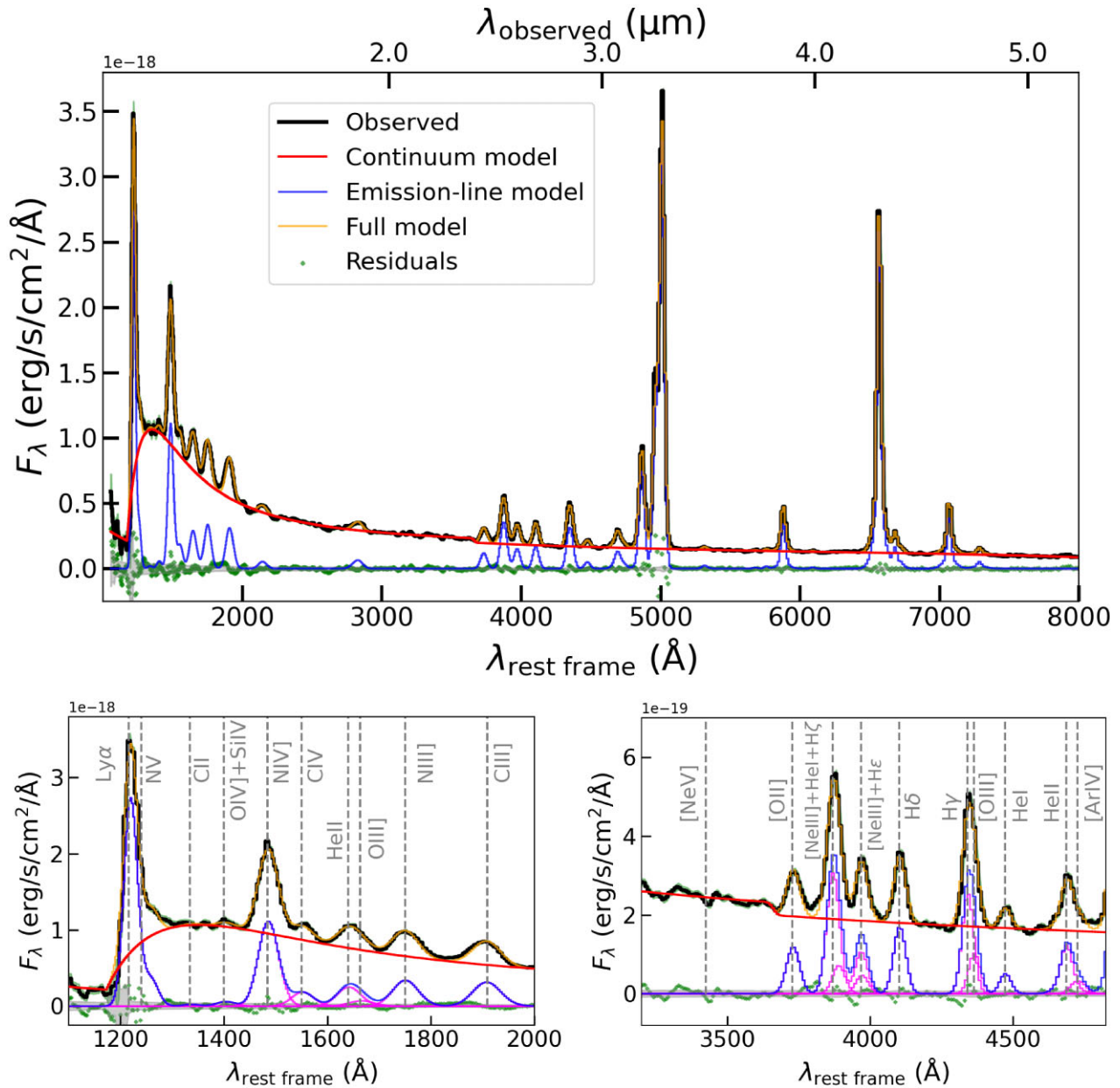


Figure 1. Best-fitting spectral model for the JWST/NIRSpec PRISM spectrum integrated from the central $0.3 \text{ arcsec} \times 0.3 \text{ arcsec}$ region of GS_3073. The solid black curve is the observed spectrum rebinned by pPXF and the surrounding shaded region indicates the rescaled 1σ uncertainty of the flux density. The solid red curve without emission lines is the continuum model. The solid orange curve on top of the continuum model is the emission line model. The solid blue curve below the observed spectrum is the emission-line only model. The green diamonds below the observed spectrum represent the residual of the fit. The grey shaded region below the observed spectrum indicates the rescaled 1σ uncertainty of the residual. *Top:* Fitting result for the PRISM spectrum across the full spectral range of 1100–8000 Å in the rest frame. *Bottom left:* Zoom-in view of the fit around the rest-frame UV lines. *Bottom right:* Zoom-in view of the fit around some relatively weak rest-frame optical lines. Fitted models for individual lines are plotted as magenta curves below the observed spectrum. The vertical dashed grey lines mark the locations of emission lines included in the model. We caution that the dashed grey lines do not mean the marked lines are detected.

from the flux calibration of the PRISM spectrum (Arribas et al. 2024; D’Eugenio et al. 2024) and different data reductions adopted for the PRISM cube we used and the G395H cube analysed by Übler et al. (2023). Also, the new reduction we adopted generated a spaxel size of $0.05 \text{ arcsec} \times 0.05 \text{ arcsec}$ for the PRISM cube, different from the previous reduction that produced a spaxel size of $0.1 \text{ arcsec} \times 0.1 \text{ arcsec}$ for the G395H cube. This potentially causes an offset between our extracted area and that in Übler et al. (2023). In addition, even if the center of the two extracted areas match exactly, the spaxels we selected near the boundary of the area would be partially outside

the extracted area of Übler et al. (2023). We performed a check by shrinking the size of the extracted aperture in the PRISM cube by one pixel and added one-pixel displacement into different directions; the resulting fluxes of $H\alpha$ and $H\beta$ are more consistent with those measured from the G395H spectrum but the $[O\text{III}]\lambda 5007$ flux is lowered by $\sim 15\text{--}20$ per cent. Regardless, most of our analyses rely on relative fluxes within the PRISM spectrum or the G395H spectrum, respectively. The only major impact of the flux difference is on the flux ratio of $[N\text{II}]\lambda 6583/[O\text{II}]\lambda 3726, 3729$, where the narrow $[N\text{II}]\lambda 6583$ is only measured in G395H and the $[O\text{II}]\lambda 3726, 3729$ is

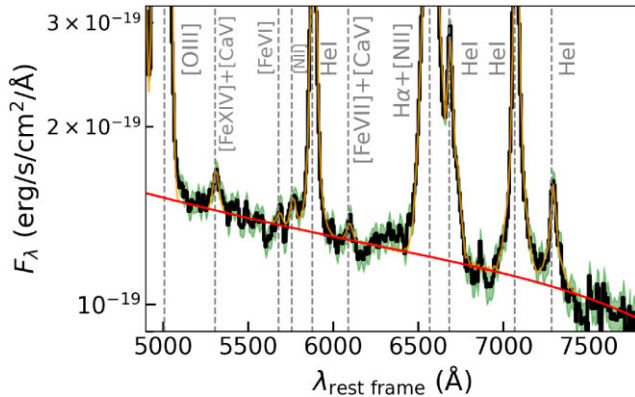


Figure 2. Zoom-in view of the best-fitting spectral model for the JWST/NIRSpec PRISM spectrum integrated from the central $0.3 \text{ arcsec} \times 0.3 \text{ arcsec}$ region of GS_3073. The flux density is displayed in log to highlight the weak lines. The solid black curve is the observed spectrum and the green shaded region indicates the rescaled 1σ uncertainty of the flux density. The solid red curve without emission lines is the continuum model. The solid orange curve on top of the continuum model is the emission line model. The vertical dashed grey lines mark the locations of emission lines included in the model.

only measured in PRISM. To account for the systematics associated with the flux mismatch, we included an extra 20 per cent systematic uncertainty for the flux ratio. As we show later, this uncertainty is smaller than the potential systematics associated with the outflowing component in these lines.

A number of lines are blended in the PRISM spectrum. In the UV, $\text{He II } \lambda 1640$ is blended with $\text{O III } \lambda \lambda 1661, 1666$. However, the blend of these lines clearly peaks close to the central wavelength of $\text{He II } \lambda 1640$ as shown in Fig. 1, suggesting its flux dominates the blend.³ The same situation applies to $\text{He II } \lambda 4686$, $[\text{Ar IV}] \lambda \lambda 4711, 4740$, and $\text{He I } \lambda 4713$, where $\text{He II } \lambda 4686$ likely dominates the blend. While it appears that $\text{N V } \lambda \lambda 1238, 1242$ is present in the PRISM spectrum, it might be blended with the red wing of $\text{Ly } \alpha$. In the next section, we used the VIMOS spectrum to check the existence of this line.

Finally, besides the $0.3 \text{ arcsec} \times 0.3 \text{ arcsec}$ extraction, we also fit the PRISM spectrum extracted from a larger aperture of $1 \text{ arcsec} \times 1 \text{ arcsec}$ in order to match the slit width of the VIMOS observation. The integrated line fluxes in general reach the maximum value with this extraction but have larger uncertainties due to the inclusion of the noisy background.

3.2 VLT/VIMOS spectrum

The VIMOS spectrum has a much higher spectral resolution compared to the PRISM spectrum. Meanwhile, the noise level of the VIMOS spectrum is higher than that of the PRISM spectrum and thus the broad component of emission lines could potentially be lost in the noise.

³We note that the wavelength sampling adopted by the data reduction pipeline we used is 50 \AA in the observed frame and 7.6 \AA in the rest frame at $z = 5.55$. We also tried resampling the spectrum to another wavelength grid as adopted in the reduction of MSA data. Despite the latter having a range of wavelength intervals from 26 to 122 \AA in the observed frame, our emission line measurements including the decomposition of blended lines remain largely unchanged.

We used PPF to fit the VIMOS spectrum. Again, we assumed the continuum is a combination of power laws. Due to the high noise level of the VIMOS spectrum, we used the best-fitting continuum model from the fitting of the PRISM spectrum to construct the input continuum template. Specifically, we fixed the relative shape of the continuum redwards of $\text{Ly } \alpha$ to that of the best-fitting PRISM continuum model, while setting the continuum bluewards of $\text{Ly } \alpha$ a flat line. This choice is motivated by the fact that the shape of the damped Lyman continuum is uncertain but it has an intrinsically low flux level. Furthermore, we did not include any polynomials during the fit in order to avoid overfitting the noise. Thus, our final continuum model is the weighted sum of a best-fitting PRISM continuum and a flat continuum in the blue.

We note that the choice of the continuum is vital for the subsequent flux measurements. For example, by assuming the underlying continuum has a stellar origin, Barchiesi et al. (2023) obtained flux measurements different from ours especially for weak lines (e.g. their flux for N V is only $\sim 1/3$ of ours). Fig. 3 shows the VIMOS spectrum and the emission lines we identified. Among the lines, $\text{Ly } \alpha$ clearly shows an asymmetric line profile. Meanwhile, N V exhibits a P-Cygni profile, which is attributed to an $\sim 3 \text{ Myr}$ -old stellar population by Barchiesi et al. (2023). Barchiesi et al. (2023) argue the feature cannot be due to absorption in the AGN continuum since GS_3073 was not confirmed to be a type-1 AGN before JWST observations and no clear absorptions in other lines were found. It is now clear from the high resolution optical spectrum that GS_3073 is a type-1 AGN (Übler et al. 2023). Still, we note that the rest-frame UV continua of many JWST-identified type-1 AGNs could have significant stellar light contributions (e.g. Harikane et al. 2023; Kocevski et al. 2023; Greene et al. 2024; Juodžbalis et al. 2024; Matthee et al. 2024). For young stellar populations at low metallicities, the UV continua are also well approximated by featureless power laws (e.g. Stanway & Eldridge 2018). The only relevant difference is whether the emission at the location of N V has a stellar continuum origin or a purely nebular origin (ionized either by stellar radiation or AGN radiation). According to the fit done by Barchiesi et al. (2023), a full stellar UV continuum model would still leave part of the N V emission nebular, indicative of the presence of highly ionized gas. We emphasize that our main conclusions are largely unchanged no matter whether we adopt a pure nebular origin for the N V emission or a partially nebular origin for the N V emission based on the results of Barchiesi et al. (2023). Even without including N V in our nebular diagnostics, we obtained similar abundance patterns, as shown in Section 4.4.

In the VIMOS spectrum, there is also detection of $\text{C II } \lambda \lambda 1334, 1335$, although it is unclear whether both lines within the doublet are present. Interestingly, while $\text{C II } \lambda 1334$ is also a resonant line similar to N V , no blueshifted absorption is visible in the spectrum. In addition, there is $\text{N IV } \lambda \lambda 1483, 1486$, and potentially $\text{O VI } \lambda \lambda 1032, 1038$ and $\text{Si IV } \lambda \lambda 1393, 1402$ in the spectrum. While the spectrum reaches the location of $\text{C IV } \lambda \lambda 1548, 1551$, the noise level becomes very high in this regime and there is no clear detection of this doublet.

Due to the complex nature of different UV lines, we adopted the following fitting strategy. First, we used three Gaussian components to approximate the asymmetric profile of $\text{Ly } \alpha$, where one narrower component is used to fit the peak of the line profile, and the other two broader components are used to capture the red wing of the line profile and thus their centroids are allowed to be redshifted with respect to that of the narrower component. We note that this multi-Gaussian fitting approach is only for estimating the total flux of $\text{Ly } \alpha$, whose profile indicates impacts from radiative transfer, and adding more Gaussian do not significantly improve the fit. Secondly, we

Table 1. Total fluxes of emission lines (in unit of 10^{-18} erg s^{-1} cm^{-2}) measured from different spectra for GS_3073.

Emission line	PRISM (0.3 arcsec \times 0.3 arcsec)	PRISM (1 arcsec \times 1 arcsec)	G395H (0.3 arcsec \times 0.3 arcsec)	VIMOS
O VI $\lambda\lambda$ 1032, 1038	–	–	–	3.6 ± 0.3^d
Ly α (total) ^a	103.3 ± 2.8	166.1 ± 4.0	–	159.6 ± 1.3
N V $\lambda\lambda$ 1238, 1242 ^a	–	–	–	9.2 ± 1.8
C II λ 1335 ^a	1.0 ± 1.6	11.9 ± 1.9	–	4.8 ± 0.6
O IV] λ 1400 + Si IV λ 1402	2.8 ± 0.9	5.4 ± 1.8	–	1.8 ± 0.4
N IV] $\lambda\lambda$ 1483, 1486	54.1 ± 0.9	65.1 ± 1.7	–	4.7 ± 0.8 (λ 1483) 22.0 ± 0.9 (λ 1486)
C IV $\lambda\lambda$ 1548, 1550	9.4 ± 1.1	13.3 ± 1.4	–	$< 37^c$
He II λ 1640 ^b	13.9 ± 0.9	16.4 ± 1.2	–	–
O III] $\lambda\lambda$ 1661, 1666 ^b	3.8 ± 0.9	$< 4.4^c$	–	–
N III] λ 1746–1754	20.7 ± 0.8	22.0 ± 1.0	–	–
C III] $\lambda\lambda$ 1906, 1908	21.0 ± 0.4	27.6 ± 0.9	–	–
N II] λ 2142	3.9 ± 0.4	5.9 ± 0.8	–	–
Mg II] $\lambda\lambda$ 2795, 2802	1.9 ± 0.3	2.9 ± 0.9	–	–
[Fe IV] $\lambda\lambda$ 2829, 2835	3.6 ± 0.4	3.9 ± 2.7	–	–
[Ne V] λ 3426	$< 0.62^c$	$< 2.0^c$	–	–
[O II] $\lambda\lambda$ 3726, 3729	7.0 ± 0.2	11.4 ± 0.3	–	–
[Ne III] λ 3869 + He I λ 3889 + H ζ	20.4 ± 0.2	28.5 ± 0.5	–	–
[Ne III] λ 3968 + H ϵ	9.8 ± 0.2	15.8 ± 0.4	–	–
H δ	9.32 ± 0.14	13.9 ± 0.5	–	–
H γ ^a	13.1 ± 0.2	19.1 ± 0.4	–	–
[O III] λ 4363 ^a	5.3 ± 0.2	7.9 ± 0.4	4.4 ± 0.6	–
He I λ 4472	2.67 ± 0.13	4.0 ± 0.3	1.4 ± 0.4	–
He II λ 4686 ^a	7.6 ± 0.3	12.7 ± 0.5	4.92 ± 0.58	–
[Ar IV] $\lambda\lambda$ 4711, 4740 + He I λ 4713 ^a	2.0 ± 0.2	0.9 ± 0.3	1.9 ± 0.4	–
–	–	–	0.39 ± 0.12 [Ar IV] (λ 4711)	–
–	–	–	0.39 ± 0.08 [Ar IV] (λ 4740)	–
H β	37.9 ± 0.2	52.5 ± 0.5	30.86 ± 0.65	–
[O III] λ 5007	146.0 ± 0.2	222.6 ± 0.3	143.63 ± 0.43	–
[Fe XIV] λ 5303 + [Ca V] λ 5309	1.1 ± 0.1	2.0 ± 0.2	–	–
[Fe VI] λ 5677	0.30 ± 0.09	$< 1.7^c$	–	–
[N II] λ 5755	0.7 ± 0.1	1.3 ± 0.2	–	–
He I λ 5876	16.4 ± 0.2	21.2 ± 0.4	13.7 ± 0.5	–
[Fe VII] λ 6087 + [Ca V] λ 6087	0.39 ± 0.09	0.31 ± 0.17	–	–
H α ^a	123.7 ± 0.3	182.1 ± 0.7	99.5 ± 1.3	–
[N II] λ 6583 ^a	$< 1.4^c$	$< 2.6^c$	2.95 ± 0.27	–
[S II] $\lambda\lambda$ 6716, 6731	1.26 ± 0.14	2.3 ± 0.3	0.42 ± 0.08	–
–	–	–	0.17 ± 0.07 (λ 6716)	–
–	–	–	0.25 ± 0.07 (λ 6731)	–
He I λ 6678	7.6 ± 0.3	12.4 ± 0.7	7.3 ± 0.5	–
He I λ 7065	21.0 ± 0.4	31.9 ± 0.6	17.0 ± 0.7	–
He I λ 7281	3.6 ± 0.3	8.7 ± 0.5	1.8 ± 0.5	–

Notes.
^a Blended with the adjacent line in the PRISM spectrum.

^b While these two lines are blended in the PRISM spectrum, the blended line profile peaks near the central wavelength of He II.

^c The value listed is the 3σ upper limit.

^d Potentially large systematic uncertainties in the continuum not taken into account.

tied the kinematics of most UV lines to that of N IV] $\lambda\lambda$ 1483, 1486, which is the strongest line besides Ly α . The kinematics of Ly α , N V $\lambda\lambda$ 1238, 1242, and C II $\lambda\lambda$ 1334, 1335 are allowed to vary with respect to those of N IV] $\lambda\lambda$ 1483, 1486 as these lines can be resonantly scattered and absorbed. Indeed, from the VIMOS spectrum, we found the peak of Ly α is redshifted with respect to that of the narrow N IV] $\lambda\lambda$ 1483, 1486 by roughly 250 km s^{-1} . Also, N V and C II show velocity shifts of roughly 1200 and 750 km s^{-1} , respectively. We did not include broad components for emission lines due to the noise. We plotted the fitting result in Fig. 3 and summarized the emission line fluxes in Table 1.

Comparing the VIMOS fluxes with the 1 arcsec-PRISM fluxes listed in Table 1, the total fluxes of Ly α measured from these spectra

are roughly consistent. However, the rest of the lines, especially the strong N IV] $\lambda\lambda$ 1483, 1486 exhibits a clear mismatch, where the PRISM flux is significantly higher. We suggest that the difference originates from a broad (BLR) component of these lines (i.e. associated with the BLR component seen in the hydrogen Balmer lines and helium lines), but undetected in the VIMOS spectrum because of the higher spectral resolution and larger noise. To check this, we convolved the VIMOS spectrum to the nominal spectrum resolution of the PRISM spectrum and resampled the VIMOS spectrum at the wavelength grid of the PRISM spectrum. We then refitted the convolved and resampled VIMOS spectrum, obtaining the total flux of the N IV] doublet to be $56.3 \pm 3.5 \times 10^{-18}$ erg/s/cm $^{-2}$, which is higher than the flux obtained from the original VIMOS spectrum but

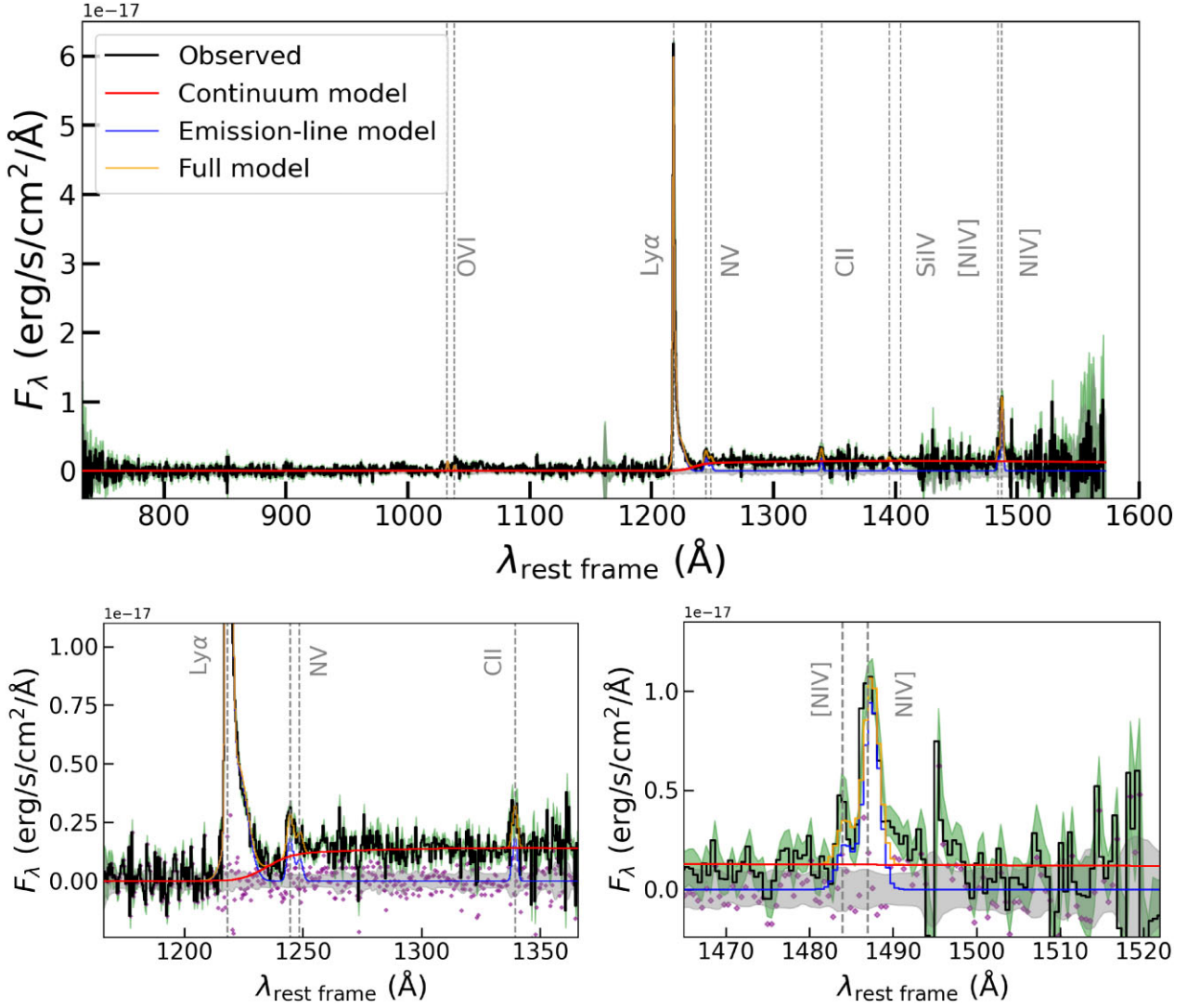


Figure 3. Best-fitting spectral model for the VLT/VIMOS spectrum measured from a 1 arcsec-wide slit. The solid black curve is the observed spectrum rebinned by PPXF and the surrounding shaded region indicates the 1σ uncertainty of the flux density. The solid red curve without emission lines is the continuum model. The solid orange curve on top of the continuum model is the emission line model. The solid blue curve below the observed spectrum is the emission-line only model. The small diamonds represent the residual of the fit. The grey shaded region below the observed spectrum indicates the 1σ uncertainty of the residual. The vertical dashed grey lines mark the locations of emission lines included in the model. *Top:* Fitting result for the VIMOS spectrum across the full spectral range of 700–1600 Å in the rest frame. *Bottom left:* Zoom-in view of the fit around Ly α , NV, and C II. *Bottom right:* Zoom-in view of the fit around N IV].

close to the flux obtained from the PRISM spectrum (c.f., Table 1). Still, we caution that the flux measurement can suffer from the following uncertainties. First, in the rebinned VIMOS spectrum, the broad wing of N IV] merges with the blue wing of C IV and is truncated at the red end of the spectrum, leading to a potential systematic associated with deblending and continuum determination. Secondly, the imperfect aperture matching and the relative flux calibrations could lead to further systematic uncertainties. By directly taking the total flux ratio of Ly α +N V and N IV], the VIMOS result is roughly 15 per cent lower than that of 1 arcsec-PRISM. However, as we show later, this systematic would only bias the abundance patterns lower, leaving our main conclusions unchanged.

Finally, as noted by Übler et al. (2023), there is a companion or an outflow component to the north-west and another one to the east of GS_3073, which would be included if the extracted size of the aperture exceeds ~ 0.3 arcsec. Based on the publicly available NIRCcam images from JADES shown in Appendix A, the north-west

and east targets are separated from the central source. The separation is clear in photometric bands including $F200W$, which essentially measures the UV continuum flux in the rest frame of GS_3073. Given the presence of continuum emission, these targets are likely satellites of the central source rather than outflows. Both the VIMOS spectrum and the 1 arcsec-PRISM spectrum can potentially have contamination from the light of these satellites.

In the following analyses, we use all the emission-line measurements listed in Table 1. Below we summarize the limitations of different measurements.

- (i) The PRISM spectrum has a spectral coverage from the rest-frame UV to the rest-frame optical. But several emission lines are blended. The G395H spectrum and the VIMOS spectrum only cover the rest-frame optical and the rest-frame UV, respectively.
- (ii) There is potentially a systematic difference between the PRISM flux and the grating flux, which varies as a function of

the wavelength. The difference can be caused by imperfect flux calibrations and different IFU cube constructions.

(iii) The VIMOS spectral measurements can suffer from an uncertain continuum model and the loss of the broad component due to the noise.

(iv) Spectra extracted from an aperture with a size larger than $0.3 \text{ arcsec} \times 0.3 \text{ arcsec}$ can have contamination from the nearby companions.

Despite these limitations, our conclusions are not significantly affected as most of our analyses do not involve flux ratios between the PRISM measurements and the G395H measurements and thus are insensitive to flux calibration issues. In addition, in the following analyses we discuss results from different extracted apertures of the PRISM cube when appropriate, and consider the potential loss of the broad component in the VIMOS spectrum.

4 NEBULAR DIAGNOSTICS

In this section, we summarize the emission-line diagnostics we performed to derive the physical conditions of the ionized gas in GS_3073. Our analyses are largely based on PYNEB (Luridiana, Morisset & Shaw 2015) and CLOUDY (Ferland et al. 2017). For calculations with PYNEB, we used atomic data from the CHIANTI data base⁴ (Dere et al. 1997; Del Zanna et al. 2021) for all relevant atoms and ions except for O^{2+} , N^{2+} , and C^{2+} . For O^{2+} , we took its transition probabilities from Tayal & Zatsarinny (2017) and collisional strengths from CHIANTI. For N^{2+} , we took its transition probabilities from Galavis, Mendoza & Zeppen (1998) and collisional strengths from CHIANTI. For C^{2+} , we took its transition probabilities from Nussbaumer & Storey (1978) and Tachiev & Froese Fischer (1999), and its collisional strengths from Berrington et al. (1985) and Keenan, Feibelman & Berrington (1992).

4.1 Dust attenuation

Our analyses are broadly separated between the rest-frame UV regime and the rest-frame optical regime. Within each spectral regime, we mostly used emission lines with similar wavelengths to perform nebular diagnostics. However, to evaluate the consistency between UV and optical diagnostics, we need to combine lines with very different wavelengths, which are therefore subject to the effect of potential dust attenuation.

In Übler et al. (2023), dust attenuation is not taken into account due to the small deviation of the Balmer decrement from the typical values found in dust-free AGNs and the analyses are limited to the optical regime. To evaluate the impact of dust on UV-to-optical line ratios, we used $\text{He II } \lambda 1640$ and $\text{He II } \lambda 4686$. These two lines are recombination lines of He and their intrinsic ratio is insensitive to variations in temperature and density. The typical intrinsic ratio of $\text{He II } \lambda 1640/\text{He II } \lambda 4686$ is 7–8, no matter whether the lines originate in H II regions, narrow-line regions (NLRs), BLRs, or stellar winds (Maschmann et al. 2024). Even with a considerable contribution from collisional excitation, as can happen in shocks, the expected intrinsic ratio of $\text{He II } \lambda 1640/\text{He II } \lambda 4686$ would still be around 6–7 (Alarie & Morisset 2019). Intriguingly, the measured $\text{He II } \lambda 1640/\text{He II } \lambda 4686$ from the 0.3 arcsec -PRISM spectrum is 1.87 ± 0.05 , significantly smaller than the intrinsic value. The ratio is even smaller in the

$\sim 1 \text{ arcsec}$ PRISM spectrum. Even if we consider the uncertainty due to blending with $\text{O III } \lambda \lambda 1661, 1666$, the measured flux ratio of $(\text{He II } \lambda 1640 + \text{O III } \lambda \lambda 1661, 1666)/\text{He II } \lambda 4686$ is 2.49 ± 0.06 . Finally, the ratio becomes 2.8 ± 0.4 if we take the $\text{He II } \lambda 1640$ flux from PRISM and the $\text{He II } \lambda 4686$ flux from G395H while ignoring the potential systematic uncertainty, still incompatible with the intrinsic ratio. The observed He II ratio reveals the dusty nature of this AGN, which is, however, not apparent from the Balmer decrement.

To estimate the magnitude of dust attenuation, we adopted an intrinsic value of $\text{He II } \lambda 1640/\text{He II } \lambda 4686 \approx 7$, typical for ionized gas with an electron temperature of $T_e \approx 1.5 \times 10^4 \text{ K}$ and an electron density of $n_e < 10^6 \text{ cm}^{-3}$. We assumed the shape of the attenuation curve to follow the shape of the average SMC extinction curve derived by Gordon et al. (2003) with $R_V = 3.1$, which can approximately describe the nebular attenuation in some galaxies at $z \sim 1-3$ (Reddy et al. 2023). While we cannot separate the broad and narrow components in $\text{He II } \lambda 1640$, the intrinsic He II ratios are similar in both the NLR and the BLR. Therefore, we further assumed the same column of dust is in the foreground of both the BLR and the NLR, and used the integrated flux for each He II line. According to Übler et al. (2023), in the R2700 spectrum, the flux of the broad $\text{He II } \lambda 4686$ is ~ 2.6 times that of the narrow $\text{He II } \lambda 4686$. If the actual attenuation is different for the NLR and the BLR, our last assumption likely makes the resulting attenuation a lower limit for the BLR. With these assumptions, we obtained $A_V = 0.49 \pm 0.01$, or $A_V = 0.39 \pm 0.01$ if we used a more conservative estimate by treating the whole $\text{He II } \lambda 1640 + \text{O III } \lambda \lambda 1661, 1666$ blend as $\text{He II } \lambda 1640$. The corresponding attenuated flux ratio of $\text{H } \alpha/\text{H } \beta$ would be ~ 3.4 assuming an intrinsic Case B ratio of 2.86. This value is slightly lower than the ratio found in the broad Balmer lines, which is 3.87 ± 0.22 according to Übler et al. (2023). Given the potential collisional excitation of the Balmer lines in the BLR, which would enhance the Balmer decrement, we considered the observed Balmer ratio consistent with both attenuation values derived from the helium lines.⁵

One might wonder whether the SMC extinction curve we adopted is appropriate for dereddening the emission lines of GS_3073. In Appendix B, we compare the measured ratio of line fluxes to the predictions by different extinction curves. In summary, if we took the total emission line fluxes measured from PRISM, which in principle correspond to the attenuation averaged between the BLR and the NLR, the He II ratio and the Balmer decrement combined favour the SMC extinction. However, if one only uses Balmer line ratios, a combination of $\text{H } \alpha/\text{H } \beta$ and $\text{H } \delta/\text{H } \beta$ would favour an average MW extinction curve given by Fitzpatrick (1999) with $R_V = 3.1$. In comparison, $\text{H } \gamma$ appears more attenuated, possibly affected by blending with $[\text{O III}] \lambda 4363$. Separating the attenuation of the BLR and the NLR is uncertain and leads to more possibilities. Regardless, in all cases, the resulting corrections for $[\text{N II}]/[\text{O II}]$ have relatively small impacts on the derived N/O, which is the abundance ratio affected most by the attenuation correction. We adopted an average value of $A_V = 0.44 \pm 0.05$ and the SMC extinction curve in the following calculations unless otherwise specified. We also discuss the case where narrow lines are actually not attenuated.

4.2 Electron temperature and density

As shown by Übler et al. (2023), the density sensitive lines $[\text{S II}] \lambda \lambda 6716, 6731$ and $[\text{Ar IV}] \lambda \lambda 4711, 4740$ are resolved in the

⁴While the version of CLOUDY, we used has an older version of CHIANTI (v7) compared to the latest version (v10) we used during the PYNEB calculations, we performed consistency checks to confirm the two data versions do not lead to noticeable difference in the predicted line ratios.

⁵The Balmer decrement would be ~ 3.6 if we assume instead an intrinsic $\text{H } \alpha/\text{H } \beta$ of 3.0 possible for AGNs (Netzer 1982).

G395H spectrum of JWST/NIRSpec. Meanwhile, [O III] λ 4363 is partially covered in the G395H spectrum (as it lies on the edge of the spectral range), whose flux is constrained by tying its kinematics with other narrow emission lines. Using [O III] λ 4363, [O III] λ 5007, and [S II] $\lambda\lambda$ 6716, 6731, Übler et al. (2023) derived an electron temperature of $T_e = 1.42^{+0.13}_{-0.15} \times 10^4$ K and an electron density of $n_e \sim 2 \times 10^3$ cm $^{-3}$. In comparison, the electron density inferred from the [Ar IV] doublet (with He I λ 4713 fitted and subtracted in G395H) is $n_e \sim 3 \times 10^3$ cm $^{-3}$. We rederived the temperature using PYNEB and obtained $T_e = 1.45 \pm 0.13 \times 10^4$ K at the low-density limit for the O $^{2+}$ zone, which translates to a temperature of $T_e = 9.4 \pm 0.1 \times 10^3$ K for the low ionization zone following the calibrations of Dors et al. (2020) based on photoionization modelling of AGN NLRs. The slight difference in the temperature is due to different choices of the atomic data base as Übler et al. (2023) used the collisional strengths from Palay et al. (2012). For consistency, we also rederived the densities. For [S II], the probability distribution of the density has a median of 2.9×10^3 cm $^{-3}$, a 16th-percentile value of 7×10^2 cm $^{-3}$, and an 84th-percentile limit of $> 10^4$ cm $^{-3}$. For [Ar IV], the probability distribution of the density has a median of 3.6×10^3 cm $^{-3}$, a 16th-percentile limit of $< 10^2$ cm $^{-3}$, and an 84th-percentile value of 1.3×10^4 cm $^{-3}$. Besides the slightly higher S/N of [Ar IV], its higher density sensitivity at high densities compared to [S II] might have allowed it to better constrain the high-density end. The temperature uncertainty induced by the 1σ uncertainty in the density traced by [Ar IV] is negligible compared to the uncertainty caused by the measurement uncertainty of [O III] λ 4363.

With the JWST/NIRSpec PRISM spectra, one can estimate the electron temperature and density probed by the rest-frame UV lines. Specifically, O III $\lambda\lambda$ 1661, 1666 can be combined with [O III] λ 5007 to estimate the temperature and N IV $\lambda\lambda$ 1483, 1486 can be used to estimate the density. However, the caveat on this approach is that O III $\lambda\lambda$ 1661, 1666 is blended with He II λ 1640 in the PRISM spectra and is the weaker line in the blend. In addition, the ratio between O III $\lambda\lambda$ 1661, 1666 and [O III] λ 5007 is sensitive to dust attenuation. Aware of these caveats, we estimated the electron temperature from the 0.3 arcsec-PRISM spectrum. Without correcting for dust attenuation, O III $\lambda\lambda$ 1661, 1666/[O III] λ 5007 gives a temperature $T_e = 1.33^{+0.05}_{-0.11} \times 10^4$ K at the low-density limit. In contrast, applying the dust attenuation drives the UV-inferred temperature to $T_e \sim 1.76$ – 1.93×10^4 K depending on the adopted A_V . The discrepancy between the temperatures inferred from O III $\lambda\lambda$ 1661, 1666/[O III] λ 5007 and [O III] λ 4363/[O III] λ 5007 can be resolved by either having an NLR less dusty than the BLR, an overestimation of the O III $\lambda\lambda$ 1661, 1666 flux due to blending, or a considerable contribution from a broad component in O III $\lambda\lambda$ 1661, 1666. It is also possible that O III $\lambda\lambda$ 1661, 1666 probes a different temperature/density zone in the NLR compared to [O III] $\lambda\lambda$ 4959, 5007 due to its higher critical density and energy level (Peimbert 1967). Finally, we note another possibility is the underestimation of the [O III] λ 4363 flux as part of the line profile is not covered by the G395H spectrum (Übler et al. 2023).

With the UV coverage, we can also estimate the electron density using the N IV $\lambda\lambda$ 1483, 1486 doublet, whose narrow component is resolved in the VLT/VIMOS spectrum. Assuming $T_e \approx 1.5 \times 10^4$ K, the density derived from [N IV] λ 1483/N IV λ 1486 is $n_e = 5.0 \pm 1.0 \times 10^5$ cm $^{-3}$, consistent with the limit obtained by Raiter et al. (2010). Increasing T_e would increase the estimate for n_e as well. For example, the electron density becomes $n_e = 6.1 \pm 1.3 \times 10^5$ cm $^{-3}$ at $T_e \approx 2 \times 10^4$ K. The density probed by N IV lines is two orders of magnitudes higher than that probed by [Ar IV] and [S II] lines, implying the narrow components of the high ionization UV lines

likely originate from a more central and denser region in the NLR. We note that there is an uncertainty associated with the continuum model for the VIMOS spectrum. By adopting a stellar continuum model, Barchiesi et al. (2023) obtained a higher ratio for [N IV] λ 1483/N IV λ 1486, which corresponds to a density of $n_e = 2.5^{+1.0}_{-0.7} \times 10^5$ cm $^{-3}$ at $T_e \approx 1.5 \times 10^4$ K. Still, in our case the underlying continuum is likely better constrained as it is constructed from the high S/N PRISM spectrum.

One might wonder whether assuming the higher density derived from N IV] can be an alternative explanation for the different temperatures derived from O III $\lambda\lambda$ 1661, 1666/[O III] λ 5007 and [O III] λ 4363/[O III] λ 5007. Assuming a uniform density of $n_e = 5 \times 10^5$ cm $^{-3}$, the attenuation corrected O III $\lambda\lambda$ 1661, 1666/[O III] λ 5007 would correspond to a temperature of $T_e \sim 1.53$ – 1.65×10^4 K, with an additional uncertainty of roughly 1000 K due to the attenuation correction. However, since the critical density of [O III] λ 5007 ($\sim 10^6$ cm $^{-3}$) is lower than that of [O III] λ 4363 ($\sim 3 \times 10^7$ cm $^{-3}$), at $n_e = 5 \times 10^5$ cm $^{-3}$, the derived temperature based on these two lines would be $T_e = 1.05^{+0.06}_{-0.08} \times 10^4$ K, leading to an even larger discrepancy. Thus, the more natural explanation would still be O III $\lambda\lambda$ 1661, 1666 partly originating in a denser and/or hotter region, possibly the BLR or the inner region of the NLR.

4.3 Oxygen abundance

With the inferred temperature from O $^{2+}$, one can estimate the oxygen abundance using narrow optical lines including [O III] λ 5007, [O II] $\lambda\lambda$ 3726, 3729, and H β , assuming the temperature for O $^{+}$ scales with that of O $^{2+}$ following the scaling relation in Dors et al. (2020), which is calibrated from photoionization models. According to Übler et al. (2023), the narrow components of He II and He I lines in the optical indicate the ionization correction factor (ICF) for O $^{2+}$ is ~ 1.017 , meaning the part of the NLR that optimally emits the optical lines barely has any higher ionization species of oxygen. As we show in the next section, this assumption no longer holds as one dives into the inner part of the NLR where high ionization lines with ionization potentials $\gtrsim 50$ eV arise.

Using only the optical lines, our calculation gives $12 + \log(\text{O}/\text{H}) \approx 12 + \log[(\text{O}^{2+} + \text{O}^{+})/\text{H}^{+}] = 8.0 \pm 0.1$, which is consistent with the value derived by Übler et al. (2023). Despite the uncertainty in the flux of O III $\lambda\lambda$ 1661, 1666, we also derived an abundance based on the attenuation-corrected flux of the doublet. Assuming $T_e \approx 1.5 \times 10^4$ K and $n_e \sim 10^3$ – 10^5 cm $^{-3}$, we obtained $12 + \log(\text{O}/\text{H}) = 8.19 \pm 0.13^6$, which is marginally larger than the result based on [O III] $\lambda\lambda$ 4959, 5007 by 1.2σ . Even taking into account these small deviations, the results are consistent with a metal-poor NLR in GS_3073. We caution that part of the observed O III $\lambda\lambda$ 1661, 1666 could come from a different zone in the NLR or even the BLR, where the ICF can significantly deviate from unity. We further discuss the potential range of ICF(O $^{2+}$) for the inner NLR in the next section.

4.4 Nitrogen abundance

In the previous sections, we have shown that the NLR in GS_3073 is likely stratified so that the optical lines originate in a less dense zone while the UV lines occupy a denser zone. In this section, we

⁶The uncertainty includes the measurement uncertainty of the flux of O III $\lambda\lambda$ 1661, 1666 and the uncertainty from the potential range of A_V .

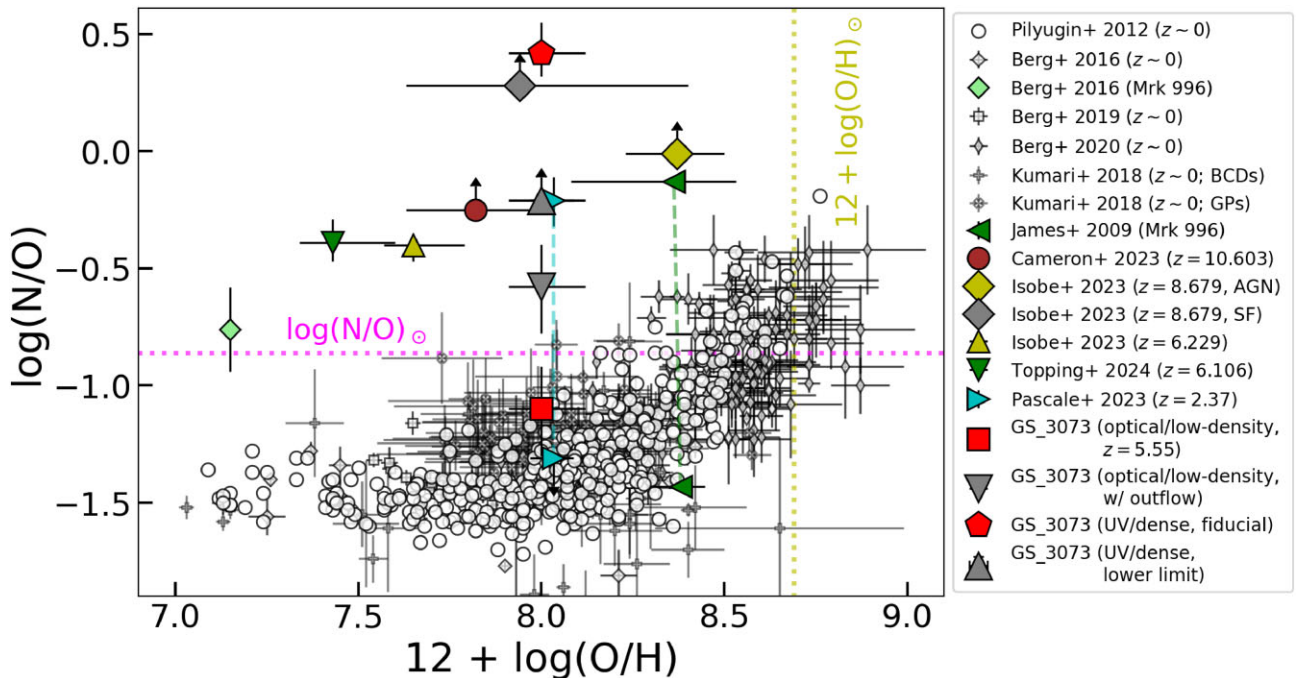


Figure 4. Relation between N/O and O/H measured from different systems. For clarity, we used open symbols to represent all $z \sim 0$ sources except Mrk 996. The open circles, diamonds, and squares are local H II regions and galaxies with abundances determined by Pilyugin et al. (2012) and Berg et al. (2016, 2019, 2020). The open plus and cross symbols represent the abundances of a sample of local blue compact dwarf galaxies (BCDs) and green pea galaxies compiled by Kumari et al. (2018). The compilation includes abundances derived by Cairós et al. (2009), James, Tsamis & Barlow (2010), James et al. (2013), Pérez-Montero et al. (2011), Westmoquette et al. (2013), Lagos et al. (2014, 2016), Kehrig et al. (2016), and Kumari et al. (2018). The abundances of the WR galaxy, Mrk 996, derived by Berg et al. (2016) are indicated by the large light-green diamond. We also show the results from James et al. (2009) for two kinematically different gas components in Mrk 996 as two left-pointing triangles connected by the dashed green line. Another source within the Sunburst Arc at $z = 2.37$ also showing two different densities and chemical abundance patterns as derived by Pascale et al. (2023) is shown as two right-pointing cyan triangles connected by the dashed cyan line. The inverted green triangle, yellow triangle, and large yellow diamond with a lower limit are nitrogen-loud galaxies at $z = 6.106$, $z = 6.229$, and $z = 8.679$, respectively, with their abundances measured by Isobe et al. (2023; also by Marques-Chaves et al. 2024) and Topping et al. (2024). The large grey diamond with a lower limit below the pentagon is the estimation by Isobe et al. (2023) assuming an SF-dominated scenario rather than an AGN-dominated scenario. The brown circle with a lower limit is an AGN candidate, GN-z11, at $z = 10.603$ with abundances estimated by Cameron et al. (2023). The red square is our estimation for GS_3073 using only the optical lines. The inverted grey triangle is also estimated based solely on optical lines, but with the assumption that a fraction of the $[\text{O II}]\lambda\lambda 3726, 3729$ is actually in the outflow. The red pentagon represents the fiducial abundances we estimated for GS_3073, where N/O is estimated from UV lines originating in a dense region. The large grey triangle corresponds to the lower limit of N/O based on UV lines, where the flux of the whole $\text{He II}\lambda 1640 + \text{O III}\lambda\lambda 1661, 1666$ is assigned to $\text{O III}\lambda\lambda 1661, 1666$. The dotted lines mark the solar abundances from Grevesse et al. (2010).

investigate this point in more detail using the nitrogen abundance inferred from different sets of emission lines.

4.4.1 N/O derived from low-critical density optical lines

We start with the optical emission lines. Again, we use the measurements from Übler et al. (2023) as $[\text{N II}]\lambda\lambda 6548, 6583$ is blended with $\text{H}\alpha$ in the PRISM spectrum. The $[\text{N II}]\lambda 6583$ flux reported in Table 1 is the sum of the narrow and outflow components, and the narrow component is better constrained as the peak of the narrow line is visible in the G395H spectrum. In what follows we used the narrow component of $[\text{N II}]\lambda 6583$ to perform the calculation, which has a flux of $1.07 \pm 0.11 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$. In order to calculate N/O, we used the following relation:

$$\text{N/O} = \frac{\text{ICF}(\text{N}^+) \text{N}^+}{\text{ICF}(\text{O}^+) \text{O}^+}. \quad (1)$$

We used both attenuation-corrected and uncorrected $[\text{N II}]\lambda\lambda 6548, 6583/[\text{O II}]\lambda\lambda 3726, 3729$ to estimate the plausible range of N^+/O^+ assuming an electron temperature of

$9.4 \pm 0.1 \times 10^3 \text{ K}$.⁷ The temperature is derived by scaling the O^{2+} temperature using the relation for NLRs in Dors et al. (2020). Then, we assumed $\frac{\text{ICF}(\text{N}^+)}{\text{ICF}(\text{O}^+)} \approx 0.8$, which is the lower limit quoted in Garnett (1990) and Izotov, Thuan & Lipovetsky (1994) but is more appropriate for NLRs (see e.g. models present in Dors et al. 2024). Adopting $\frac{\text{ICF}(\text{N}^+)}{\text{ICF}(\text{O}^+)} \approx 1$ typically assumed for H II regions would only increase the resulting N/O by 0.1 dex, which does not change our overall conclusion. With these assumptions, we derived $\log(\text{N/O}) = -1.1 \pm 0.1$, where the uncertainty mainly comes from whether the attenuation correction is applied or not. As shown in Fig. 4, the N/O ratio we obtained from optical (forbidden) lines is overall consistent with the N/O versus O/H relation found in the nearby H II regions and SF galaxies (especially GPs that are considered to be local analogues of high- z galaxies; Kumari et al. 2018). If $[\text{O II}]\lambda\lambda 3726, 3729$ has a significant outflow component contributing a fractional flux similar to that in the $[\text{N II}]\lambda 6583$, the

⁷Again, we note the attenuation correction could lead to an underestimation of N^+/O^+ as the attenuation derived from He II could be biased towards the BLR.

resulting N/O would lie above the local relation as indicated by the inverted grey triangle symbol.

We note that there is also a tentative detection of the auroral line [N II] λ 5755 in the PRISM. This line is marginally detected in the G395H spectrum. If we ignore the potential systematic difference between the PRISM flux and G395H flux and calculate the temperature for N⁺ using [N II] λ 5755/[N II] λ 6583, the result would be $T_e \gtrsim 3.0 \times 10^4$ K at the low density limit, which is inconsistent with the temperature for the low-ionization zone derived above. If one assumes instead the regions traced by N IV], [N II], and all the other species have a common density of $n_e \approx 5 \times 10^5$ cm⁻³, the N⁺ temperature is lowered to $T_e = 1.02_{-0.08}^{+0.07} \times 10^4$ K, as [N II] λ 6583 would have been collisionally deexcited significantly. However, this uniform density model would also lower the O²⁺ temperature significantly and lead to a corresponding N⁺ temperature of 8.6×10^3 K following the scaling relation of Dors et al. (2020), making the whole scenario self-inconsistent. A potential contaminant for [N II] λ 5755 is [Fe II] λ 5747. Based on photoionization calculations with CLOUDY (c17.03, Ferland et al. 2017), we found the flux of [Fe II] λ 5747 would be $\lesssim 10$ per cent of that of [N II] λ 5755 for Fe/O values up to solar. Whereas the flux of [Fe II] λ 5747 needs to be roughly 10 times that of [N II] λ 5755 to make the temperatures agree. Again, we caution that the above derivation would be affected by the flux difference between PRISM and G395H, the flux measurement of [N II] λ 5755 can be affected by the broad component of the adjacent He I line which is not easy to model (see Fig. 2), the continuum model (which has been assumed to be a smooth power law), and [N II] λ 5755 might still have an unresolved component coming from the high-density region where [N II] λ 6583 has significant collisional de-excitation. Given these sources of systematic uncertainties, we did not use the [N II] λ 5755-based temperature derived above.

There is another low-ionization line, N II] λ 2142, detected in the UV as listed in Table 1. However, since N II] λ 2142 has a critical density of 9.4×10^9 cm⁻³ that is significantly higher than that of [O II], it can have contributions from the BLR and the dense part the NLR. In addition, a large UV attenuation correction would be needed if one uses N II]/[O II].

4.4.2 N/O derived from high-critical density UV lines

Next, we calculated the N/O ratio using UV emission lines. The presence of strong N III], N IV], and N V lines in the UV indicate a significant fraction of nitrogen is in high ionization states. The complicating factor of the calculation is the potential contribution from the broad component in the PRISM spectrum and that the N V line is only resolved in the VIMOS spectrum.

To start with, we diagnosed the ionization state of the ionized gas in GS_3073 using photoionization models. We used a set of fiducial models for SF regions, NLRs of AGNs, and BLRs of AGNs. All models are generated by CLOUDY (c17.03, Ferland et al. 2017) and have the same range of metallicity and ionization parameter. The range of the metallicity is set to $Z/Z_\odot \sim 5 \times 10^{-4} - 2$. The ionization parameter is defined as $U \equiv \Phi_0/n_H c$, where Φ_0 is the number flux of photons capable of ionizing hydrogen, n_H is the hydrogen density, and c is the speed of light. The range of the ionization parameter is set to $U \sim 10^{-3.5} - 10^{-1}$. For the chemical abundance patterns, we started by scaling N/O with O/H following the empirical relation fitted by Groves, Dopita & Sutherland (2004) using a sample of local SF galaxies and H II regions, which can roughly reproduce the relative fluxes of [N II] λ 6583 measured in the Seyfert 2 population from the Sloan Digital Sky Survey IV/Mapping Nearby Galaxies at Apache Point Observatory Survey (SDSS IV/MaNGA; Bundy et al.

2015; Yan et al. 2016; Ji & Yan 2020). This relation is given by

$$N/O = 10^{-1.6} + 10^{2.33 + \log(O/H)}. \quad (2)$$

We then scaled the carbon abundance by the same factor such that [C/O] = [N/O]. The helium abundance was scaled using the relation adopted by Dopita et al. (2000). We emphasize that the above choices of the scaling relations have little impact on our following diagnostics on the ionization properties.

For SF models, we set $n_H = 200$ cm⁻³ while adopting an isobaric equation of state (EoS). We used an spectral energy distribution (SED) from a simple stellar population (SSP) generated by the Binary Population and Spectral Synthesis code (BPASS; Stanway & Eldridge 2018; Byrne et al. 2022), assuming the default parameters and a starburst 1 Myr ago. We included dust and dust depletion with the default depletion factors given by CLOUDY. For completeness, we also ran SF models with a density of $n_H = 5 \times 10^5$ cm⁻³, which do not change our conclusions.⁸

For NLR models, we set $n_H = 5 \times 10^5$ cm⁻³. We note that the diagnostics we show in the following is relatively insensitive to the density. We also tried $n_H = 10^3$ cm⁻³ and our conclusion remains unchanged. We set the SED as a canonical AGN SED that has an effective big blue bump temperature of $T_{BB} = 10^6$ K, a UV-to-X-ray slope of -1.4 , a UV slope of -0.5 , and an X-ray slope of -1.0 . The UV spectral shape of GS_3073 is in rough agreement with the corresponding part of the AGN SED we adopted, although we note that any dust attenuation for the continuum would mean an intrinsically steeper UV slope or a greater stellar light contribution in the UV. We also checked analytical AGN SED models from Pezzulli et al. (2017) with the black hole mass and the range of Eddington ratios similar to those derived by Übler et al. (2023). We show in Appendix C that our conclusions remain largely unchanged. The rest of the parameters are the same as the SF models.

Finally, we generated the BLR models by setting $n_H = 10^{11}$ cm⁻³ and assuming an isopycnic EoS. We also checked BLR models with $n_H = 10^9$ cm⁻³ and $n_H = 10^{10}$ cm⁻³ and the diagnostic results remain largely the same. The density range we considered cover the plausible range for BLR clouds showing strong semiforbidden transitions (10^8 cm⁻³ < n_H < 10^{12} cm⁻³, Netzer 1990). We did not include dust and dust depletion for the BLR models, and we computed two sets of BLR models with hydrogen column densities of $N(H) = 10^{23}$ cm⁻² and $N(H) = 10^{25}$ cm⁻², respectively. The former value of $N(H)$ is typically adopted in photoionization modelling of the BLR emission (e.g. Netzer 1990; Baldwin et al. 2004; Temple et al. 2021), the latter is a plausible value for BLRs with Compton-thick clouds, which is a potential explanation for the X-ray weakness of many JWST-identified type-1 AGN including GS_3073 (Juodžbalis et al. 2024; Maiolino et al. 2024a). The rest of the parameters are the same as the NLR models.

In the left panel of Fig. 5, we plot a hardness diagram composed of line ratios from N III], N IV], and N V. The location of any given data point in this diagram is insensitive to the chemical abundances of the gas and it is sensitive primarily to the shape of the ionizing SED and the ionization parameter. The location in the diagram would also depend, to a lesser extent, on the density of the gas. One can see AGN models occupy a region very different from the SF models in this diagram due to their overall harder ionizing SED. We also plot the observed line ratios of GS_3073. The fiducial line ratios we adopted (the green star) is a combination of PRISM measurements

⁸The line ratios predicted by the high density SF models are actually more significantly different from the observed ratios.

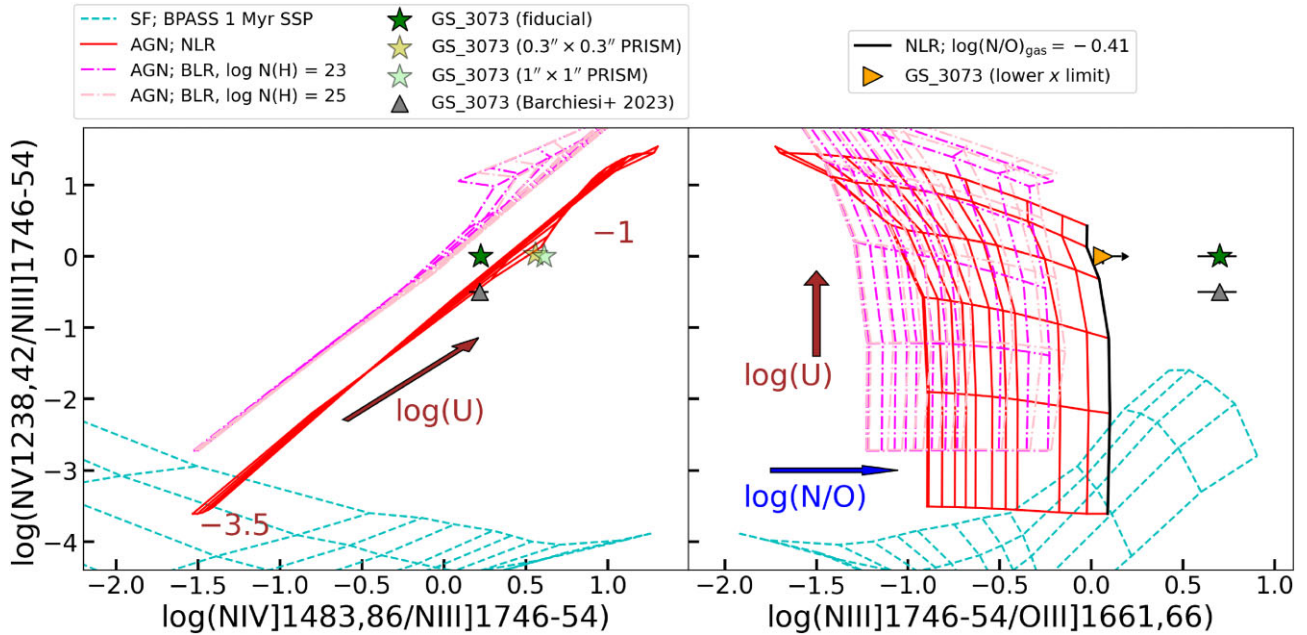


Figure 5. *Left:* Line ratios predicted by different photoionization models together with the observed line ratios of GS_3073 in the $N\text{v}/N\text{III}]$ versus $N\text{IV}] / N\text{III}]$ diagram. The dashed cyan grid, solid red grid, and the dotted–dashed magenta and pink grids represent photoionization models for SF regions, NLRs of AGNs, and BLRs of AGNs. All model grids span the same range of metallicity and ionization parameter, with $Z/Z_{\odot} \sim 5 \times 10^{-4} - 2$ and $U \sim 10^{-3.5} - 10^{-1}$. The arrow indicates the increasing direction of U for the models. The solid green star is the fiducial measurements we adopted for GS_3073. The transparent yellow and light green stars replace the narrow $N\text{IV}]$ measured from VIMOS with the $N\text{IV}]$ measured from the PRISM with different apertures. The grey triangle replaces $N\text{v}$ and $N\text{IV}]$ with the measurements by Barchiesi et al. (2023), which assume a stellar origin for the UV continuum. *Right:* Line ratios predicted by different photoionization models together with the observed line ratios of GS_3073 in the $N\text{v}/N\text{III}]$ versus $N\text{III}] / O\text{III}]$ diagram. The arrows indicate the increasing directions of U and N/O for the models. The solid black line in the rightmost of the NLR grid represents models with a gas-phase nitrogen abundance of $\log(N/O)_{\text{gas}} = -0.41$. The right-pointing triangle represents a lower limit for N/O set by replacing the flux of $O\text{III}]$ with the summed flux of $\text{He II}\lambda 1640$ and $O\text{III}]$. The rest of the symbols are the same as the left panel.

and VIMOS measurements, where $N\text{v}$ and $N\text{IV}]$ are taken from the narrow-line measurements from VIMOS and $N\text{III}]$ is taken from the PRISM.⁹ Overall the observed line ratios are consistent with the fiducial NLR models. While the $N\text{III}]$ might have an unresolved broad component, reducing the $N\text{III}]$ flux would only push the data point towards the upper right location, consistent with a more highly ionized NLR. We also tried plotting the data point by adopting the $N\text{IV}]$ fluxes measured from the 0.3 arcsec-PRISM spectrum and the 1 arcsec-PRISM spectrum, the resulting locations (yellow and light green stars) in the diagram are still consistent with the NLR models. Finally, we tried replacing the $N\text{v}$ and $N\text{IV}]$ fluxes with the measurements by Barchiesi et al. (2023), who used a continuum model of a stellar origin to fit the VIMOS spectrum. It is clear that the resulting location (grey triangle) in the diagram is still more consistent with an AGN origin rather than a stellar origin.

We revisited here several measurement systematics that might impact the above ionization analyses. The first one is matching the intrinsic apertures of VIMOS and PRISM observations. Since the JWST observation has an intrinsically smaller PSF compared to that of the VLT, the aperture matched line ratios should lie between those using the 0.3 arcsec- and 1 arcsec-PRISM extractions. The second one is the contamination from the broad component of $N\text{III}]$. From the left panel of Fig. 5, it is clear that any of such contamination would only bias the data point closer to the SF models. Finally, for the relative flux calibration, since both the $\text{Ly}\alpha$ fluxes and the

$N\text{IV}]$ fluxes are similar between the (resolution degraded) VIMOS measurements and PRISM measurements (see Section 3.2), the corresponding systematic bias is unlikely to be significant. Although the broad $N\text{v}$, similar to the broad $N\text{IV}]$, might be lost in the VIMOS spectrum, this does not impact our analyses here.

In the right panel of Fig. 5, we diagnosed the N/O of GS_3073 by comparing its UV line ratios with those predicted by photoionization models. In this $N\text{v}/N\text{IV}]$ versus $N\text{III}] / O\text{III}]$ diagram, the y -axis traces primarily the hardness of the ionizing SED as well as the ionization parameter, while the x -axis traces the abundance ratio of N/O . The fiducial line ratios we adopted are composed of $N\text{v}$ measured from VIMOS, and $N\text{III}]$ and $O\text{III}]$ measured from PRISM. One uncertainty therefore comes from the broad-line contribution to $N\text{III}]$ and $O\text{III}]$. By comparing the BLR and NLR models, one can see at the same N/O , the BLR has a lower $N\text{III}] / O\text{III}]$. Therefore, the broad component would only bias the observed $N\text{III}] / O\text{III}]$ to a lower value, meaning our measured $N\text{III}] / O\text{III}]$ is potentially a lower limit. Another uncertainty is the flux of $O\text{III}]$ as it is blended with $\text{He II}\lambda 1640$ in PRISM and it is the weaker line of the blend. Still, we have shown that the fitted flux of $O\text{III}]$ gives a reasonable estimate of the electron temperature. If we considered a very extreme case where the blend is actually dominated by $O\text{III}]$, which would require $O\text{III}]$ to be blueshifted by $\sim 4000 \text{ km s}^{-1}$ and significant dust attenuation, the data would still suggest a super solar N/O as shown by the orange triangle in Fig. 5.

However, we note that the comparison made on the right panel of Fig. 5 uses models where N/O is varied accordingly with O/H following Groves et al. (2004). Since oxygen is a major

⁹The $N\text{III}]$ fluxes measured from the 0.3 arcsec aperture and the 1 arcsec aperture are very similar as shown by Table 1.

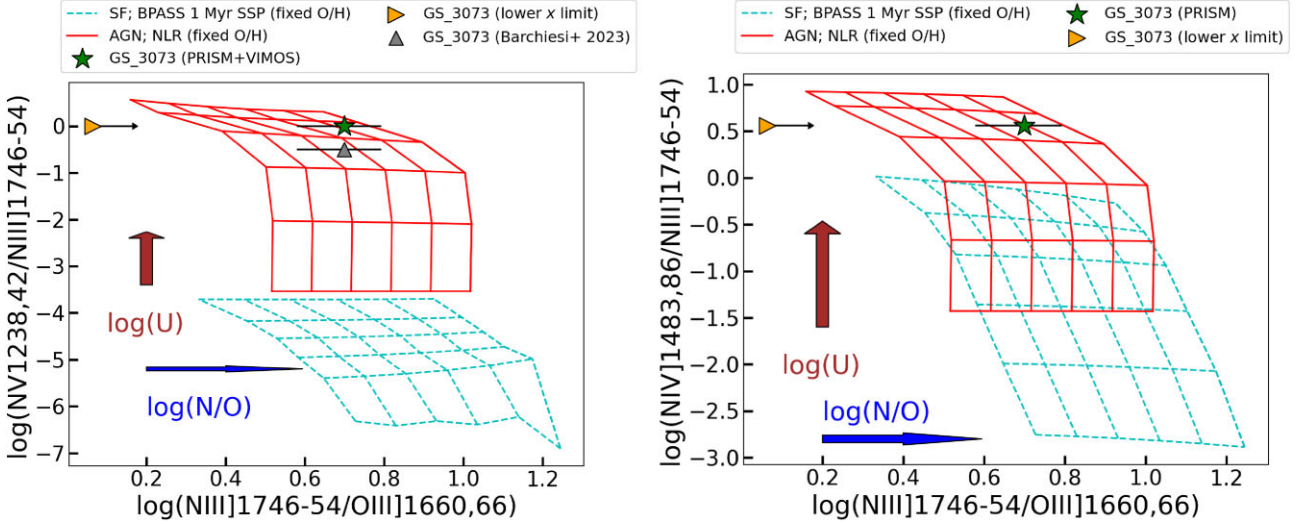


Figure 6. *Left:* Diagnostic diagram composed of $N\text{ v}/N\text{ III}]$ and $N\text{ III]}/O\text{ III}]$. The photoionization models shown have a fixed metallicity of $12 + \log(O/H) = 8.0$ and $\log(N/O)$ ranging from 0.03 to 0.53 dex. The rest of the model parameters are the same as the corresponding models in Fig. 5. The green star represents the fiducial line ratios we measured for GS_3073. The grey triangle replaces the $N\text{ v}$ flux with that measured by Barchiesi et al. (2023) assuming the UV continuum is stellar dominated. The right-pointing orange triangle set the lower x -axis limit by assigning the whole $\text{He II}\lambda 1640 + O\text{ III]}\lambda\lambda 1661, 1666$ flux to $O\text{ III]}\lambda\lambda 1661, 1666$. *Right:* Diagnostic diagram composed of $N\text{ IV]}/N\text{ III}]$ and $N\text{ III]}/O\text{ III}]$. The models shown are the same as the ones on the left panel. The green star and the right-pointing orange triangle represent measurements from the 0.3 arcsec-PRISM spectrum only.

coolant of the ionized gas and we have constrained the oxygen abundance, we make a more appropriate comparison by fixing the metallicity¹⁰ to be $12 + \log(O/H) = 8.0$ while varying N/O in Fig. 6. We used a range of N/O from roughly 0.89 dex above solar to 1.29 dex above solar. By interpolating the model grid linearly in $\log(N/O)$ and $\log(U)$ using the GRIDDATA function from the SCIPY package, we found the best-fitting NLR model points have $\log(U) = -1.7^{+0.2}_{-0.1}$ and $\log(N/O)_{\text{gas}} = 0.45^{+0.08}_{-0.13}$. The best-fitting values become $\log(U) = -2.2 \pm 0.1$ and $\log(N/O)_{\text{gas}} = 0.27^{+0.09}_{-0.13}$ if we adopt Barchiesi et al. (2023)'s measurements instead. If no attenuation corrections are applied, the above values become $\log(U) = -2.1 \pm 0.1$ and $\log(N/O)_{\text{gas}} = 0.34^{+0.10}_{-0.15}$ for the higher nebular $N\text{ v}$ flux, and $\log(U) \approx -2.5$ and $\log(N/O)_{\text{gas}} = 0.26^{+0.10}_{-0.11}$ for the lower nebular $N\text{ v}$ flux.

From this figure, we can also estimate the potential impact from contamination by SF regions. Based on our models, low-density SF regions tend to produce significantly lower $N\text{ v}/N\text{ III}] \lesssim -3.7$ and slightly higher $N\text{ III]}/O\text{ III}]$ at the same N/O . Thus, there are two effects. On one hand, the intrinsic N/O would be slightly lower due to the contamination in $N\text{ III]}/O\text{ III}]$. On the other hand, the intrinsic $N\text{ v}/N\text{ III}]$ would be higher for the NLR, leading to a higher N/O at a fix $N\text{ III]}/O\text{ III}]$. The above effects work in opposite directions and their relative importance depends on the details of the contamination. As a first-order approximation, we added an extra 0.1 dex systematic uncertainty for the model-based N/O in quadrature accounting for these effects. If we assumed instead the SF contamination is strong in the UV and thus $N\text{ IV}]$ has an origin from high-density SF regions with $n_{\text{H}} = 5 \times 10^5 \text{ cm}^{-3}$, we obtained even lower $N\text{ v}/N\text{ III}] \lesssim -4$ and higher N/O at fixed $N\text{ III]}/O\text{ III}]$, such that our measured $N\text{ III]}/O\text{ III}]$ would correspond to $\log(N/O)_{\text{SF;gas}} \sim 0.43$ at $\log(U) \sim -1$. Thus, the above analyses remain largely unchanged.

¹⁰Besides oxygen, the rest of the elements are scaled by the same factor except for nitrogen and carbon. The carbon abundance is set using the value derived later.

One might also wonder whether the diagnostics involving $N\text{ v}$ above might be biased by resonant scattering. While it is difficult to quantify the effect of resonant scattering, its contribution to the observed $N\text{ v}$ in broad absorption line quasars (BALQSOs) has been examined previously (e.g. Hamann & Korista 1996; Wang et al. 2010). As shown by Hamann & Korista (1996), the theoretical scattered profiles of $N\text{ v}$ in BALQSOs are relatively broad even compared to the BLR component and the resonant scattering contributes up to ~ 31 per cent of the flux. Although narrower profiles are plausible (Wang et al. 2010), they are still considerably broader compared to the BLR component of GS_3073, while what we measured from the VIMOS spectrum is a narrow component. Thus, in our case, if the nebular $N\text{ v}$ originates in gas close to AGN, it is not unreasonable to assume little contribution from the resonant scattering to the observed $N\text{ v}$. We also emphasize that $N\text{ v}$ is not essential for the abundance determination. In the right panel of Fig. 6, we replace $N\text{ v}/N\text{ III}]$ with $N\text{ IV]}/N\text{ III}]$ in the y -axis. While SF and AGN model grids become closer along the y -axis in this diagram, by matching the data point to the AGN model grid, we obtained a similar N/O and U as found in the $N\text{ v}/N\text{ III}]$ versus $N\text{ III]}/O\text{ III}]$ diagram.

To crosscheck the N/O inferred from CLOUDY models, we used PYNEB to calculate the relative abundances of different ionization species of nitrogen. We calculated N^{2+}/O^{2+} , N^{3+}/O^{2+} , and N^{4+}/O^{2+} from our fiducial flux ratios of $N\text{ III]}/O\text{ III}]$, $N\text{ IV]}/O\text{ III}]$, and $N\text{ v}/O\text{ III}]$ measured in the rest-frame UV, respectively. We set the density to $n_e = 5 \times 10^5 \text{ cm}^{-3}$ as inferred from $N\text{ IV}]$, and set the temperature to $T_e = 1.45 \times 10^4 \text{ K}$. We obtained $\log\left(\frac{N^{4+}+N^{3+}+N^{2+}}{O^{2+}}\right) = 0.67^{+0.12}_{-0.10}$ with dust attenuation corrections and $\log\left(\frac{N^{4+}+N^{3+}+N^{2+}}{O^{2+}}\right) = 0.58^{+0.12}_{-0.09}$ without dust attenuation corrections. We note that varying the density in the range of $n_e \sim 10^3\text{--}10^5 \text{ cm}^{-3}$ would vary the result by ~ 0.01 dex and varying the temperature in the range of $T_e \sim 10^4\text{--}2 \times 10^4 \text{ K}$ would vary the result by ~ 0.1 dex.

Now the remaining step is to calculate ICFs to account for the unobserved ions, which depend both on the shape of the ionizing SED as well as the ionization parameter of the ionized gas. We estimated

Table 2. Gas-phase chemical abundances derived from the JWST/NIRSpec and VLT/VIMOS spectra of GS_3073*.

Abundance	Value	n_e (cm ⁻³)	T_e (K)	log(U)
12+log(O/H)	$8.00^{+0.12}_{-0.09}$	$< 10^4$	$1.45 \pm 0.13 \times 10^4$	–
log(N/O) _{Optical} ^a	$-1.10^{+0.18}_{-0.20}$ (w/o outflow)	$< 10^4$	$9.4 \pm 0.1 \times 10^3$	–
	$-0.58^{+0.18}_{-0.20}$ (w/ outflow)	$< 10^4$	$9.4 \pm 0.1 \times 10^3$	–
log(N/O) _{UV; Low} ^b	$> -0.21^c$	$5.0 \pm 1.0 \times 10^5$	$1.8\text{--}2.1 \times 10^4$	$-1.7^{+0.2}_{-0.1}$
log(N/O) _{UV; Fiducial} ^b	$0.42^{+0.13}_{-0.10}$	$5.0 \pm 1.0 \times 10^5$	$1.8\text{--}2.1 \times 10^4$	$-1.7^{+0.2}_{-0.1}$
log(N ²⁺ /O ²⁺)	0.28 ± 0.10	$5.0 \pm 1.0 \times 10^5$	1.8×10^4	–
log(N ³⁺ /O ²⁺)	0.02 ± 0.10	$5.0 \pm 1.0 \times 10^5$	2.0×10^4	–
log(N ⁴⁺ /O ²⁺)	-0.46 ± 0.14	$5.0 \pm 1.0 \times 10^5$	2.1×10^4	–
log(C/O) _{UV; Low}	$> -1.01^c$	$5.0 \pm 1.0 \times 10^5$	$1.7\text{--}2.0 \times 10^4$	$-1.7^{+0.2}_{-0.1}$
log(C/O) _{UV; Fiducial}	$-0.38^{+0.13}_{-0.11}$	$5.0 \pm 1.0 \times 10^5$	$1.7\text{--}2.0 \times 10^4$	$-1.7^{+0.2}_{-0.1}$
log(C ²⁺ /O ²⁺)	-0.30 ± 0.10	$5.0 \pm 1.0 \times 10^5$	1.7×10^4	–
log(C ³⁺ /O ²⁺)	-1.13 ± 0.11	$5.0 \pm 1.0 \times 10^5$	2.0×10^4	–
log(Fe ⁶⁺ /Ne ⁴⁺)	$> -1.08 - -0.48$	$5.0 \pm 1.0 \times 10^5$	2.0×10^4	$-1.7^{+0.2}_{-0.1}$
log(Fe/O)	$> -1.84 - -1.24$ ([Fe VII])	$5.0 \pm 1.0 \times 10^5$	–	–
	-1.74 ± 0.05 ([Fe IV])	$5.0 \pm 1.0 \times 10^5$	–	–

Notes.

* Assuming the physical conditions from AGN NLR models. See Section 4 for discussions on the impact of different ionized regions.

^a Calculated based on [N II]/[O II] in the optical.

^b Calculated based on N V, N IV], N III], and O III] in the UV.

^c Assuming O III] has the flux of the whole He II+O III] blend (see Section 4).

the ICFs using the photoionization models that match the observed line ratios of GS_3073 best as shown in Fig. 6. As we have discussed, the measured UV line ratios are consistent with a highly ionized NLR, whose ionization parameter is $\log(U) = -2.1 \sim -1.7$. The ICF for oxygen inferred from the NLR models that match the fiducial line ratios of GS_3073 is $\text{ICF}(\text{O}^{2+}) \sim 2$. Meanwhile, the ICF for nitrogen is $\text{ICF}(\text{N}^{2+}, \text{N}^{3+}, \text{N}^{4+}) \sim 2$, which is similar to $\text{ICF}(\text{O}^{2+})$. Applying the ICFs leads to $\log(\text{N}/\text{O}) \sim 0.57$ with dust attenuation corrections and $\log(\text{N}/\text{O}) \sim 0.63$ without dust attenuation corrections.

Last but not least, a major concern with the above PYNEB calculation is the assumption of a single-temperature zone, which is not valid even for a single isobaric cloud. Ideally, the higher ionization species would arise in a zone with a higher electron temperature in the NLR, resulting in a higher emissivity at a fixed abundance. To correct for the temperature stratification, we again used photoionization models and applied the temperature relations for different ionic species at $\log(U) = -2.1 \sim -1.7$. The temperatures for different ions predicted by the models lie in a range of $1.8\text{--}2.1 \times 10^4$ K. The temperature-corrected abundance ratio is $\log(\text{N}/\text{O}) = 0.42^{+0.13}_{-0.10}$ when the lines are attenuation corrected, about 0.15 dex lower than the estimate based on a uniform temperature. This result is consistent with the direct comparison with photoionization models in Fig. 6. When no attenuation corrections are applied, the result becomes $\log(\text{N}/\text{O}) = 0.53^{+0.11}_{-0.10}$. In Table 2, we list N/O measured through different methods as well as the ionic nitrogen abundances. It is clear that the dominant ion of nitrogen is N^{2+} .

We note that we did not consider N II] λ 2142 due to the complexity associated with the unknown temperature and density of the low ionization zone as well as the dust attenuation correction. In general, the inclusion of N II] λ 2142 would make the final N/O even higher if one assumes a lower temperature as appropriate for the low ionization zone. Similar to other semiforbidden transitions, N II] λ 2142 can have contributions from the BLR due to its high critical density.

In Fig. 4, we show the N/O measurements from both the UV lines and optical lines, respectively. The high N/O derived from UV lines (with attenuation corrections) clearly place GS_3073 in the category of the nitrogen-loud AGN. For comparison, we also plotted several

nitrogen-loud targets at high redshifts identified with JWST data (Cameron et al. 2023; Isobe et al. 2023; Topping et al. 2024).

An extremely interesting result for GS_3073 is the different N/O ratios from optical (forbidden) lines with low critical densities and UV (permitted or semi-forbidden) lines. One might wonder whether this discrepancy implies any systematic bias in the ionization corrections for optical lines, where only N^+ is probed. However, if the optical [N II] and [O II] lines all originate from the same high-density cloud as the UV lines, the ionization correction ratio based on the photoionization models at $\log(U) \sim -2$ becomes $\text{ICF}(\text{N}^+)/\text{ICF}(\text{O}^+) \approx 0.26$ for the dense NLR model and $\text{ICF}(\text{N}^+)/\text{ICF}(\text{O}^+) \approx 0.35$ for the dense SF model. Furthermore, since [O II] has a lower critical density compared to [N II], their emissivity ratio decreases at the high density, leading to a lower N^+/O^+ given the observed flux ratio of [N II]/[O II]. As a result, the N/O based on the measured flux ratio of [N II]/[O II] is even lower compared to the currently adopted value and the discrepancy remains.

An alternative explanation is that the UV line emitting region somehow does not contribute to the low critical density and low ionization lines such as [N II] and [O II]. This can either be due to the UV line emitting regions are more dust obscured, being density bounded thereby missing the partially ionized zone, or having a further density stratification such that even N IV] does not reflect the true average density. Meanwhile, the UV line emitting region is more nitrogen enhanced compared to the low-density and low-ionization region. While this chemical stratification is not unexpected for AGNs, there has been little direct observational evidence, especially at such high redshifts. We further discuss the implications of these results in Section 5.

4.5 Carbon abundance

The rich spectral information of GS_3073 allows the determination of the chemical abundances for elements other than nitrogen and oxygen. The joint determinations of multiple elemental abundances can better constrain the enrichment mechanisms of the observed

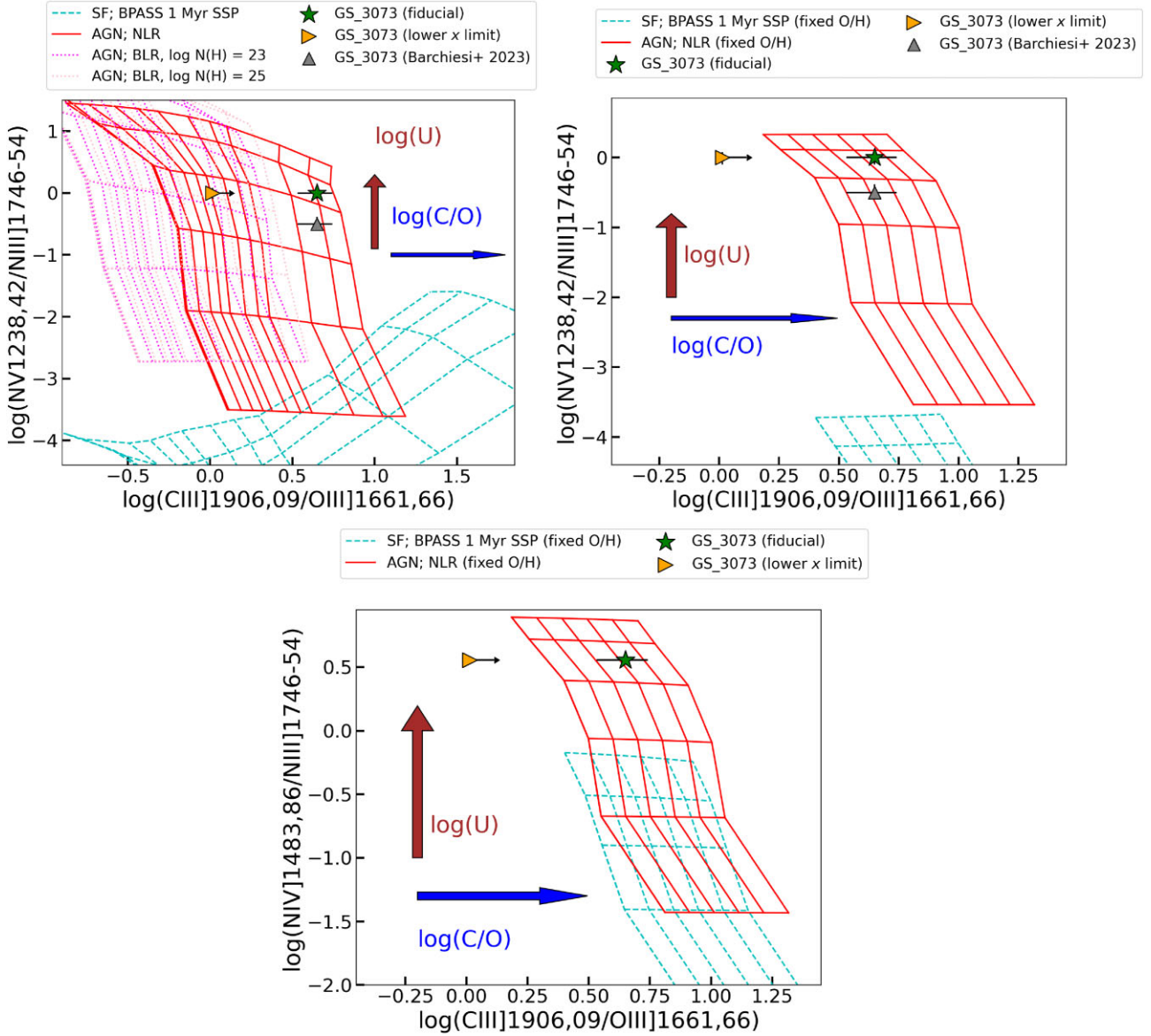


Figure 7. *Upper left:* Diagnostic diagram composed of $N\text{v}/N\text{III}]$ and $C\text{III}]/O\text{III}]$. The photoionization models are the same as those in Fig. 5. The green star represents the fiducial line ratios we measured for GS_3073. The grey triangle replaces the $N\text{v}$ flux with that measured by Barchiesi et al. (2023) assuming the UV continuum is stellar dominated. The right-pointing orange triangle set the lower limit for C/O by assigning the whole $\text{He}\text{II}\lambda 1640 + O\text{III}]\lambda\lambda 1661, 1666$ flux to $O\text{III}]\lambda\lambda 1661, 1666$. The rightmost two vertical model lines of the NLR grid correspond to $\log(C/O)_{\text{gas}} = -0.32$ and $\log(C/O)_{\text{gas}} = -0.21$, respectively. *Upper right:* The models shown have a fixed metallicity of $12 + \log(O/H) = 8.0$, a fixed nitrogen abundance of $\log(N/O) = 0.43$, and a range of carbon abundances of $-0.5 \leq \log(C/O) \leq 0$. *Bottom:* Diagnostic diagram composed of $N\text{IV}]/N\text{III}]$ and $C\text{III}]/O\text{III}]$. The models shown are the same as those in the upper right panel. The green star and the right-pointing orange triangle represent measurements from the 0.3 arcsec-PRISM spectrum only.

region and thus can provide additional clues for the origin of the nitrogen loudness.

In the rest-frame UV spectrum of PRISM, there is detection of $C\text{IV}$ and $C\text{III}]$ lines. Combining these lines with $O\text{III}]$, we can roughly estimate the carbon abundance. We found no detection of $C\text{II}]\lambda\lambda 2324, 2325$ in the UV. While there is detection of $C\text{II}]\lambda\lambda 1334, 1335$ in the VIMOS spectrum, due to the complex nature of the doublet¹¹ and the fact that it is unresolved in the spectrum, we did not estimate the carbon abundance using this line.

¹¹Within the doublet, $C\text{II}]\lambda 1334$ is a resonant line and $C\text{II}]\lambda 1335$ is a fluorescent line.

We note that the observed peak of $C\text{II}$ is redshifted with respect to the peak of $N\text{IV}]\lambda\lambda 1483, 1486$ in the VIMOS spectrum, potentially indicating the presence of an outflow. Another complicating factor for estimating the total carbon abundance is that the region occupied by C^+ extends beyond the H^+ region and goes into the photodissociation region (PDR). Thus, the fractional contribution from C^+ has a sensitive dependence on the boundary condition of the ionized cloud.

Fig. 7 shows a comparison between photoionization models and the observed line ratios of GS_3073 in the $N\text{v}/N\text{III}]$ versus $C\text{III}]/O\text{III}]$ diagram. The fiducial line ratios of GS_3073 match a range of abundance ratios from $\log(C/O)_{\text{gas}} \sim -0.32$ to $\log(C/O)_{\text{gas}} \sim -0.21$ when C/O is scaled with O/H as described in Section 4.4. When O/H and N/O is fixed and C/O is varied, as shown on the upper right panel

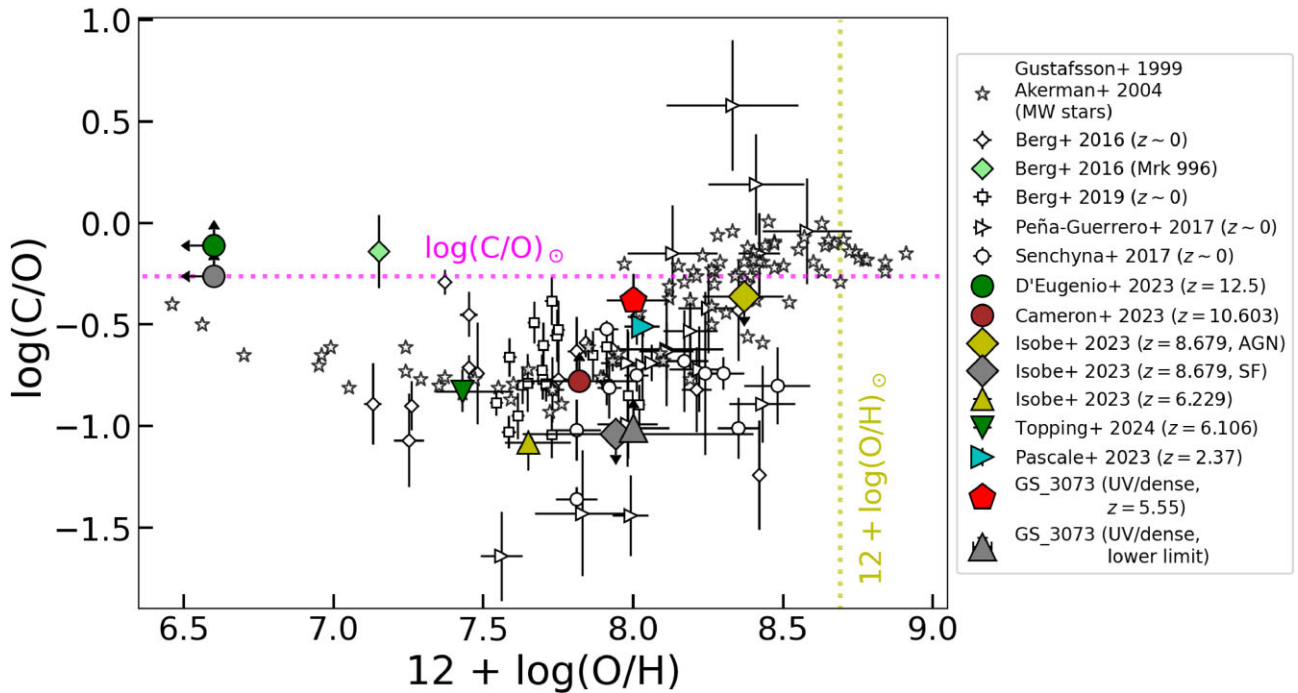


Figure 8. Relation between C/O and O/H measured from different systems. For clarity, we used open symbols to represent all $z \sim 0$ sources except Mrk 996. The open stars are Milky Way (WM) stars with abundances determined by Gustafsson et al. (1999) and Akerman et al. (2004). The small open diamonds, squares, triangles, and circles are local H II regions and galaxies with abundances determined by Berg et al. (2016, 2019), Peña-Guerrero et al. (2017), and Senchyna et al. (2017). The large light-green diamond is Mrk 996, a metal-poor blue compact dwarf galaxy showing WR features. The right-pointing cyan triangle represents the abundances of gas surrounding a super-star cluster in the Sunburst Arc at $z = 2.37$ measured by Pascale et al. (2023). The large inverted green triangle, large yellow triangle, and large yellow diamond are nitrogen-loud galaxies at $z = 6.106$, $z = 6.229$, and $z = 8.679$, respectively, with their abundances measured by Isobe et al. (2023; also by Marques-Chaves et al. 2024) and Topping et al. (2024). The grey diamond beside the large triangle is the estimation by Isobe et al. (2023) assuming an SF-dominated scenario rather than an AGN-dominated scenario. The brown circle with a lower limit is a nitrogen-loud AGN candidate, GN-z11, at $z = 10.603$ with abundances estimated by Cameron et al. (2024). The large green and grey circles in the leftmost of the sequence correspond to a carbon rich galaxy, GS-z12, at $z = 12.5$, with abundances constrained by D’Eugenio et al. (2023) with different assumptions. The red pentagon represents the fiducial abundances we estimated for GS_3073, where C/O is estimated from UV lines. The large grey triangle corresponds to the lower limit of C/O based on UV lines, where the flux of the whole He II $\lambda 1640 + \text{O III} \lambda \lambda 1661, 1666$ is assigned to O III $\lambda \lambda 1661, 1666$. The dotted lines mark the solar abundances from Grevesse et al. (2010).

of Fig. 7, with attenuation corrections, the best-fitting NLR parameters are $\log(U) = -1.7^{+0.2}_{-0.1}$ and $\log(\text{C/O})_{\text{gas}} = -0.15^{+0.13}_{-0.16}$ for the fiducial measurements, and $\log(U) = -2.2 \pm 0.1$ and $\log(\text{C/O})_{\text{gas}} = -0.30^{+0.14}_{-0.15}$ for the measurements based on those of Barchiesi et al. (2023). The abundances above became $\log(\text{C/O})_{\text{gas}} = -0.18^{+0.13}_{-0.16}$ (high $\log(U)$) and $\log(\text{C/O})_{\text{gas}} = -0.26^{+0.15}_{-0.14}$ (low $\log(U)$) if no attenuation corrections were applied. While the stellar nebular emission contamination as inferred from the SF model predictions would lead to less than 0.1 dex bias in C/O at similar U , we included a systematic uncertainty of 0.1 dex in the values above as a conservative estimation. We note that dielectronic recombination is important for C III] when $T_e > 10^4$ K, which is another source of uncertainty.¹² Finally, any BLR contribution would lead to underestimation of C/O as C III] is suppressed relative to O III]. Similar to the analyses on N/O, we replaced N V/N III] in the upper right panel of Fig. 7 with N IV]/N III] in the bottom panel of Fig. 7. Again, we obtained a similar value of C/O by matching the AGN model grid with the data point.

We also estimated C/O based on PYNEB. To circumvent the C^+ problem, if we assumed in the ionization zone occupied by O^{2+} that carbon is mainly in C^{2+} and higher ionization species, we obtained $[(\text{C}^{2+} + \text{C}^{3+} + \text{C}^{4+} + \dots)/(\text{C}^{2+} + \text{C}^{3+})]/[(\text{O}^{2+} + \text{O}^{3+} + \dots)/\text{O}^{2+}] \approx$

$0.70\text{--}0.72$ from the best-fitting NLR models, where the range of the value corresponds to $\log(U) = -2.2\text{--}-1.7$. The equation above only corrects for missing ionization species that are more than doubly ionized. We note that by computing the full ICF into the C^+ zone, we obtained a similar value of $\text{ICF}(\text{C}^{2+}, \text{C}^{3+})/\text{ICF}(\text{O}^{2+}) \approx 0.7$, although in this case a significant fraction of C and O comes from singly ionized and neutral species. This leads to $\log(\text{C/O}) = -0.38^{+0.13}_{-0.11}$ (high $\log(U)$) and $\log(\text{C/O}) = -0.42^{+0.13}_{-0.11}$ (low $\log(U)$). The PYNEB value based on our fiducial measurements with a high $\log(U)$ is lower than the CLOUDY value by 1.1σ . The difference might come from the assumption of multiple uniform-temperature zones made in the PYNEB calculation as well as the adopted ICF. The derived abundances are listed in Table 2. We note that C^{2+} traced by C III] is significantly more abundant than C^{3+} traced by C IV. If we only used C III]/O III] to get the abundance, we obtained $\log(\text{C}^{2+}/\text{O}^{2+}) = -0.30 \pm 0.10$ and $\text{ICF}(\text{C}^{2+})/\text{ICF}(\text{O}^{2+}) \approx 1.2$ at $\log(U) = -1.7$. This gives $\log(\text{C/O}) = -0.24 \pm 0.10$, which is more consistent with the model result. This comparison indicates the observed C IV is weaker compared to the model prediction, potentially due to the resonant scattering and self-absorption of C IV.

Fig. 8 shows the C/O versus O/H relation found in galaxies and stars. One can see the fiducial carbon abundance of GS_3073 is only slightly higher compared to other systems with similar metallicities, and the lower limit on the carbon abundance is also compatible with the local relation. Compared to nitrogen, carbon appears less

¹²In CLOUDY simulations, the dielectronic recombination is calculated with rate coefficients from <http://amdpp.phys.strath.ac.uk/tamoc/DR/>.

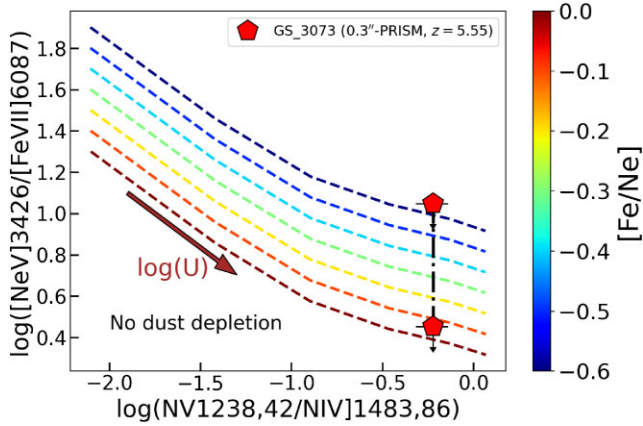


Figure 9. Diagnostic diagram composed of $N\text{ V}/N\text{ IV}]$ and $[\text{Ne V}]/[\text{Fe VII}]$. The dashed coloured lines are photoionization models with parameters similar to the NLR models shown in Fig. 5 but having different abundance ratios of F/Ne , where $[\text{Fe}/\text{Ne}]$ ranges from -0.6 to 0 dex from top to bottom. All models shown have no dust or dust depletion. The pentagons represent the line ratios measured from the 0.3 arcsec-PRISM and VIMOS spectra, with the $[\text{Ne V}]/[\text{Fe VII}]$ being the 3σ upper limit. The higher upper limit was obtained assuming the blended line around 5303 \AA is dominated by $[\text{Ca V}]$, and the lower upper limit was obtained assuming the blended line around 5303 \AA is dominated by $[\text{Fe XIV}]$. The plausible range for the actual upper limit is indicated by the vertical dash-dotted line.

enriched. Indeed, normal carbon abundances have been observed in a number of nitrogen-loud AGNs and galaxies. The AGN candidate at the highest redshift observed by JWST, GN-z11, also shows a lower limit in C/O compatible with the local C/O versus O/H relation (Cameron et al. 2023). In addition, two nitrogen-loud galaxies at $z \sim 6$ with abundances determined by Isobe et al. (2023) and Topping et al. (2024) also exhibit C/O compatible with local systems, as shown in Fig. 8. We further discuss the implication of a normal C/O in a nitrogen-loud system in Section 5.

4.6 Iron abundance

Iron is another useful element for constraining the enrichment mechanism due to the specific production channels. Despite being an abundant element, Fe lines are usually difficult to observe due to the significant depletion in dust of Fe in the ISM, which typically leaves only ~ 1 per cent of Fe in the gas phase (Jenkins 2009). Meanwhile, due to the complicated ICFs for Fe species, the gas-phase Fe abundance is difficult to constrain accurately in observations (e.g. Rodríguez & Rubin 2005). In this section, we tried estimating the relative abundance of Fe by using abundance indicators including Fe lines.

From Fig. 1 and Table 1, one can see several Fe lines are potentially detected in the PRISM spectrum. The most significant detection is in $[\text{Fe XIV}]\lambda 5303$, which, however, is blended with $[\text{Ca V}]\lambda 5309$. We note that this blend has already been reported as marginally detected in the JWST/NIRSpec G395H spectrum by Übler et al. (2023). The detection of the high ionization line $[\text{Fe XIV}]\lambda 5303$ was previously reported in a number of AGN at lower redshift (e.g. Osterbrock 1981; Penston et al. 1984; Ward & Morris 1984; Alloin et al. 1992; Rose, Elvis & Tadhunter 2015). Osterbrock (1981), for example, reported detection of the $[\text{Fe XIV}]\lambda 5303 + [\text{Ca V}]\lambda 5309$ blend in the Seyfert 1 galaxy III ZW 77. By measuring the centroid of the blended line profile, which is at $5307.4 \pm 0.4 \text{ \AA}$ in the rest frame of III ZW 77, Baldwin, Phillips & Terlevich (1981) concluded

that $[\text{Fe XIV}]\lambda 5303$ should be present in the spectrum, otherwise the blend should have a centroid around 5309.2 \AA . We performed a similar check by measuring the line centroid

of the blend with pPXF assuming it is a single Gaussian. With 500 times of bootstrap similar to the flux measuring procedure (see Section 3), we obtained a line center at $5306.3^{+3.7}_{-3.6} \text{ \AA}$ in the rest frame of other narrow emission lines of GS_3073. While the line profile is not centering at $[\text{Ca V}]\lambda 5309$, the difference is not significant. We also note that the inclusion of a potential nearby line, $[\text{Fe VI}]\lambda 5335$, would change the line center. If we include $[\text{Fe VI}]\lambda 5335$ and tie its kinematics to those of other narrow lines, the resulting line centroid of the $[\text{Fe XIV}]\lambda 5303 + [\text{Ca V}]\lambda 5309$ blend would be at $5300.0^{+3.6}_{-4.3} \text{ \AA}$. Regardless, although $[\text{Fe XIV}]\lambda 5303$ is potentially present in the spectrum, the S/N and the spectral resolution prevent us from drawing a definite conclusion.

Due to the high ionization potential of Fe^{12+} , $[\text{Fe XIV}]\lambda 5303$ is classified as a coronal line that arises from a highly ionized and dense region of the AGN. Another coronal line frequently observed in AGNs is $[\text{Fe VII}]\lambda 6087$. Due to the similar ionization potentials of Fe^{5+} ($98.985 \pm 0.015 \text{ eV}$) and Ne^{3+} ($97.1900 \pm 0.0025 \text{ eV}$), Fe^{6+} ($124.9671 \pm 0.0025 \text{ eV}$) and Ne^{4+} ($126.247 \pm 0.012 \text{ eV}$) (from the National Institute of Standards and Technology Atomic Spectra Database, Kramida et al. 2023), and the similar critical densities of $[\text{Fe VII}]\lambda 6087$ ($4.46 \times 10^7 \text{ cm}^{-3}$) and $[\text{Ne V}]\lambda 3426$ ($1.90 \times 10^7 \text{ cm}^{-3}$), their ratio is a useful diagnostic of the Fe abundance in AGNs. In GS_3073, however, we did not detect $[\text{Ne V}]\lambda 3426$.¹³ Thus, we calculated a 3σ upper limit on the flux ratio of $[\text{Ne V}]\lambda 3426/[\text{Fe VII}]\lambda 6087$ and used this to estimate the abundance ratio of Ne/Fe . A complicating factor here is the contamination from $[\text{Ca V}]\lambda 6087$, whose strength is roughly fixed to be $1/5$ of $[\text{Ca V}]\lambda 5303$ as they have the same upper level. In AGNs with coronal line detections, $[\text{Ca V}]\lambda 6087$ is usually much weaker compared to $[\text{Fe VII}]\lambda 6087$ (e.g. Rose et al. 2015). This can be understood as Ca is more significantly depleted on to dust grains compared to Fe, as inferred from the observations of the ISM in the Galaxy (e.g. Crinklaw, Federman & Joseph 1994). Regardless, we consider below two extreme cases where the 5303 \AA blend is dominated by $[\text{Fe XIV}]\lambda 5303$ and $[\text{Ca V}]\lambda 5309$, respectively. In the latter case, $[\text{Fe VII}]\lambda 6087$ would have a flux of $1.6 \pm 0.9 \times 10^{-19} \text{ erg s}^{-1} \text{ cm}^{-2}$ for the 0.3 arcsec-PRISM extraction, thus no longer significantly detected. We use the following equation to estimate the 3σ upper limit of the flux ratio $[\text{Ne V}]\lambda 3426/[\text{Fe VII}]\lambda 6087$

$$F_{[\text{Ne V}]} / F_{[\text{Fe VII}]} < 3 \sqrt{\left(\frac{\sigma_{[\text{Ne V}]}}{F_{[\text{Fe VII}]}} \right)^2 + \left(\frac{\sigma_{[\text{Fe VII}]} \sigma_{[\text{Ne V}]}}{F_{[\text{Fe VII}]}} \right)^2}, \quad (3)$$

where we have replaced the mean of $F_{[\text{Ne V}]}$ using the 1σ formal uncertainty as a conservative estimation, and the fluxes are corrected for dust attenuation as described in Section 4.1.

As shown in Fig. 9, by comparing NLR models with different abundance ratios of Ne/Fe (with O/H , N/O , and C/O fixed to the values derived in Section 4) to the observed line ratios, we can roughly estimate the Ne/Fe of GS_3073. Specifically, based on the less noisy $0.3 \text{ arcsec} \times 0.3 \text{ arcsec}$ extraction of the PRISM cube, the two upper limits on the attenuation-corrected flux ratio of

¹³The non-detection of $[\text{Ne V}]$ seems common in the current JWST-identified low-luminosity AGN sample, no matter being type-1 or type-2 (e.g. Maiolino et al. 2024c; Scholtz et al. 2023). While such a lack of $[\text{Ne V}]$ might not be unexpected based on the analyses of Cleri et al. (2023), the implication of this result requires more quantitative analyses and is beyond the scope of this work.

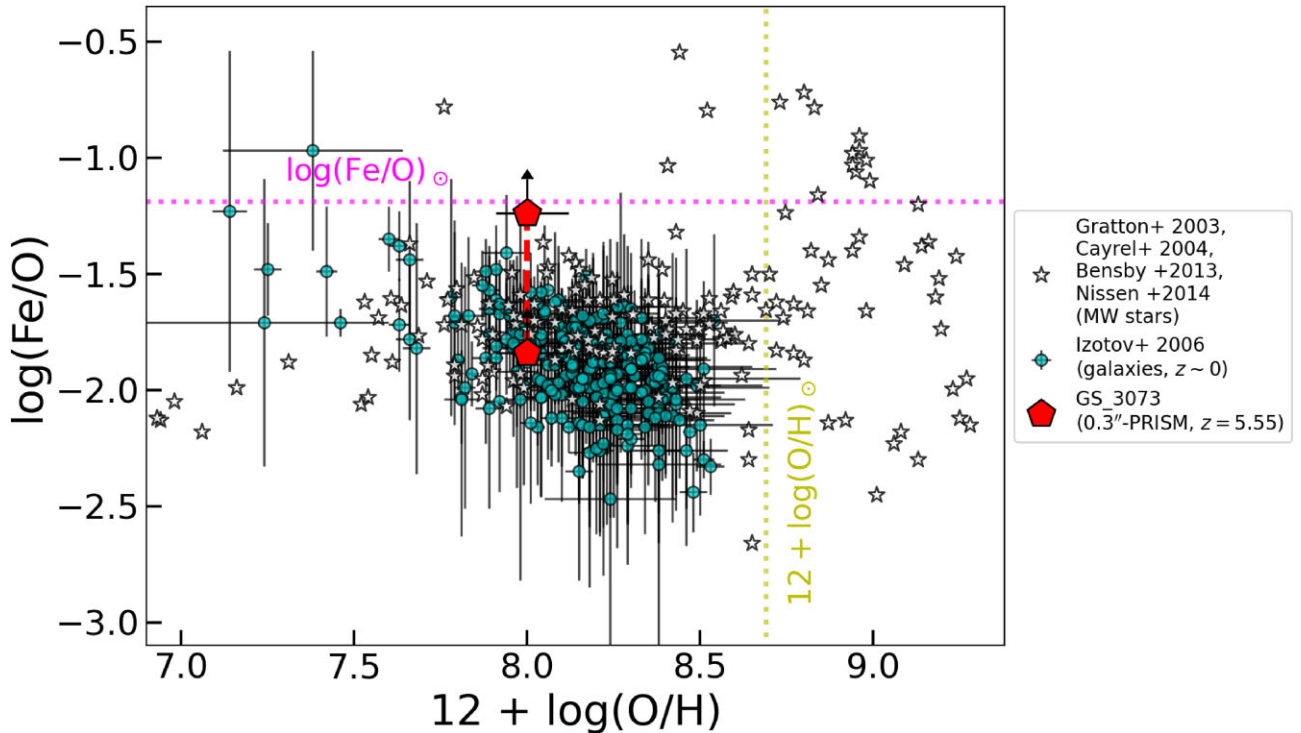


Figure 10. Relation between Fe/O and O/H measured from different systems. The open stars are MW stars with abundances determined by Gratton et al. (2003), Cayrel et al. (2004), Bensby et al. (2013), and Nissen et al. (2014). The small cyan circles are local metal-poor galaxies with abundances determined by Izotov et al. (2006). The red pentagon represents the abundances we estimated for GS_3073. The dotted lines mark the solar abundances from Grevesse et al. (2010). Based on the derived upper limits, the abundance ratio of Fe/O of GS_3073 can be either similar to or higher than those of the local systems with similar O/H.

$[\text{Ne V}]\lambda 3426/[\text{Fe VII}]\lambda 6087$ implies $[\text{Ne}/\text{Fe}] \lesssim 0.65$ and $[\text{Ne}/\text{Fe}] \lesssim 0.05$, respectively, assuming no dust depletion. Unlike Fe, Ne is in general not depleted on to dust grains in the ISM. Thus, if there is dust depletion, the intrinsic abundance ratio of Ne/Fe is even lower. While there is clear evidence for the presence of dust based on the observed $\text{He II}\lambda 1640/\text{He II}\lambda 4686$, it is possible that the region hosting coronal lines, such as $[\text{Fe VII}]\lambda 6087$, has the dust destroyed due to the high temperature and intense ionizing radiation. We note that the reason we chose NLR models rather than BLR models is in part due to the fact that the critical densities of $[\text{Ne V}]$ and $[\text{Fe VII}]$ ($\sim 10^7 \text{ cm}^{-3}$) are lower than the typical densities of broad-line emitting clouds ($\gtrsim 10^8 \text{ cm}^{-3}$; Netzer 1990). It is suggested that the coronal-line emitting regions are likely more extended than the BLR but more compact compared to the bulk of the NLR (e.g. Nagao et al. 2003), although there is also observational evidence that they can be more extended (Negus et al. 2021). To check the density, we further computed BLR models with a density of $n_{\text{H}} = 10^8 \text{ cm}^{-3}$ and a column density of $N_{\text{H}} = 10^{23} \text{ cm}^{-2}$, and dense NLR models with a density of $n_{\text{H}} = 10^7 \text{ cm}^{-3}$. We found our estimations are largely unchanged even with these high density models.

We can convert the constraint on Ne/Fe to Fe/O by estimating Ne/O from emission lines of $[\text{Ne III}]\lambda 3968$ and $[\text{O III}]\lambda 5007$. The ionization potential of Ne^+ is close to that of O^+ . In the optical, the narrow emission lines suggest oxygen is mostly in O^{2+} (Übler et al. 2023). Therefore, to a first-order approximation, we have $\text{Ne}/\text{O} \approx \text{Ne}^{2+}/\text{O}^{2+}$. This estimation would then only apply to the ionization zone occupied by optical narrow lines. In the optical, although $[\text{Ne III}]\lambda 3968$ is blended with $\text{H}\epsilon$ in PRISM, we can estimate the flux of $\text{H}\epsilon$ using the Case B ratio of $\text{H}\epsilon/\text{H}\beta$ modulated by dust attenuation. From $[\text{Ne III}]\lambda 3968$ and $[\text{O III}]\lambda 5007$, we obtained $[\text{Ne}/\text{O}] \equiv \log(\text{Ne}/\text{O}) - \log(\text{Ne}/\text{O})_{\odot}$ to range from 0.22 to 0 for a range of n_{H} from 10^3 cm^{-3} to $5 \times$

10^5 cm^{-3} . Given that oxygen can be depleted on to dust grains by ~ 0.22 dex in the ISM (Jenkins 2009), the result is compatible with an intrinsic stellar Ne/O being near-solar or super-solar. In either case, the resulting lower limit on Fe/O would be near-solar or super-solar. In Fig. 10, we compare the Fe/O of GS_3073 with those in local metal-poor galaxies and MW stars (Gratton et al. 2003; Cayrel et al. 2004; Izotov et al. 2006; Bensby et al. 2013; Nissen et al. 2014). From this comparison, one can see GS_3073 has an Fe/O ratio either similar to or higher than those of local stars and galaxies with similar O/H ratios.

Additional evidence for the plausible value of Fe/O can be found through another significantly detected Fe line, $[\text{Fe IV}]\lambda\lambda 2829, 2835$ (which are fitted together as a single Gaussian, see Table 1). The ionization potentials of Fe^{2+} and Fe^{3+} are $30.651 \pm 0.012 \text{ eV}$ and $54.91 \pm 0.04 \text{ eV}$, which are close to those of O^+ ($35.12112 \pm 0.00006 \text{ eV}$) and O^{2+} ($54.93554 \pm 0.00012 \text{ eV}$) (Kramida et al. 2023). Using the attenuation corrected flux ratio of $[\text{Fe IV}]\lambda\lambda 2829, 2835/[\text{O III}]\lambda 5007$, we obtained $[\text{O}/\text{Fe}] \approx 0.5$ (see Appendix D), consistent with the range derived from $[\text{Ne V}]\lambda 3426/[\text{Fe VII}]\lambda 6087$. However, one caveat of using $[\text{Fe IV}]\lambda\lambda 2829, 2835/[\text{O III}]\lambda 5007$ is that $[\text{Fe IV}]\lambda\lambda 2829, 2835$ has a much higher critical density ($\sim 10^8 \text{ cm}^{-3}$) compared to that of $[\text{O III}]\lambda 5007$ ($9.39 \times 10^5 \text{ cm}^{-3}$), and thus their emitting regions are not necessarily tightly co-spatial.

Another caveat of the above analysis is the coronal-line region might have a different abundance pattern compared to the optical NLR, which we further discuss in the next section.

5 DISCUSSION

In this section, we discuss the implications of the derived physical conditions for GS_3073.

5.1 Enrichment mechanism

5.1.1 Enrichment of nitrogen and carbon

In Table 2, we summarize the chemical abundances that we have derived for GS_3073. The chemical abundance pattern of GS_3073 shows an exceptionally enriched nitrogen abundance with respect to the oxygen abundance. While AGB stars can preferentially raise the abundance ratio of N/O in the ISM (e.g. Nomoto, Kobayashi & Tominaga 2013, and references therein), their enrichment usually lags behind that of CCSNe, which preferentially boost the relative abundance of oxygen in the ISM. As a result, the abundance pattern in typical galaxies would follow the trend shown by local H II regions and SF galaxies in Fig. 4.

As noted by Isobe et al. (2023), the relative abundances of carbon and nitrogen in the nitrogen-loud high-redshift systems confirmed by JWST are similar to those of nitrogen-enhanced metal-poor stars and metal-poor globular cluster (GC) stars. Thus, Isobe et al. (2023) suggest these JWST systems are potential progenitors of GCs. Still, the actual enrichment mechanism is uncertain and people have suggested enrichment by WR stars (Senchyna et al. 2024; Kobayashi & Ferrara 2024; Watanabe et al. 2024), ejecta from AGB stars combined with inflows of pristine gas (D’Antona et al. 2023), VMSs with stellar masses of $100 M_{\odot} < M < 1000 M_{\odot}$ (Vink 2023), SMSs with stellar masses of $M \gtrsim 10^3 M_{\odot}$ (Charbonnel et al. 2023; Nagele & Umeda 2023), and TDEs (Cameron et al. 2023). In all the above cases, the nitrogen-enriched (and potentially carbon-enriched) outermost layers of stars are stripped via stellar winds or interactions with black holes to enrich the surrounding ISM.

While the above-enrichment mechanisms can all produce a high N/O in the early Universe in a metal-poor environment, the predictions on the abundance ratio of N/C differ among them. As shown by the chemical enrichment models of Isobe et al. (2023) and Watanabe et al. (2024), while SMSs preferentially lead to an abundance pattern with $\log(\text{N}/\text{O}) \gtrsim -0.2$ and $\log(\text{C}/\text{O}) \gtrsim -0.8$, WR stars and TDEs produce a wide range of abundance patterns with $\log(\text{N}/\text{O}) \lesssim 0.6$ and $\log(\text{C}/\text{O}) \lesssim -0.3$. Purely judging from the abundance ratios of N/O and C/O of GS_3073, the enrichment by SMSs or WR stars is plausible (Limongi & Chieffi 2018; Nagele & Umeda 2023; Watanabe et al. 2024). For the enrichment purely by AGB ejecta, the equilibrium abundance ratios of N/O and C/O from the CNO cycle are generally higher than the JWST-confirmed nitrogen-loud sources including GS_3073 ($\log(\text{N}/\text{O})_{\text{CNO equil.}} \sim 1$, $\log(\text{C}/\text{O})_{\text{CNO equil.}} \sim -0.5$ – -0.3 ; Maeder, Meynet & Chiappini 2015). However, if the gas is initially slightly enriched in oxygen and is later mixed with pristine gas, the observed range of N/O and C/O of the JWST-confirmed nitrogen-loud sources can be reproduced by AGB enrichment models (D’Antona et al. 2023). Finally, for VMSs, calculations by Vink (2023) show they are capable of reproducing the range of N/O inferred for GN-z11 but full chemical evolution models including VMSs remain to be developed.

An important question is the physical scale as well as the time-scale of the enrichment required to explain the observations. Take the highest redshift AGN candidate, GN-z11, as an example. It is possible that the nitrogen-loudness is limited to the BLR of the AGN, which would then only require a few stars to enrich a physical region of $\sim 10^{-2}$ pc (Maiolino et al. 2024b). However, confirmations of broad-line AGNs become increasing difficult at early times due to the decreasing masses of SMBHs (Maiolino et al. 2024b, c). Another nitrogen-loud galaxy, CEERS_01019 at $z = 8.679$, is also classified as an AGN based on the presence of high ionization lines (Isobe et al. 2023). In the case of the nitrogen-loud galaxy, RXC

J2248-ID, at $z = 6.106$, Topping et al. (2024) argue the ionization is SF-dominated and thus the enrichment is likely galactic-wide. While there is a clear broad component underlying H α in the spectrum of RXC J2248-ID, Topping et al. (2024) argue for an outflow origin as a broad component is also found in [O III] λ 5007, although weaker and with a different profile. In addition, the strength of He II λ 1640 is weaker than the predictions of AGN photoionization models. Finally, for the last high-redshift nitrogen-loud target shown in Fig. 5, GLASS_150008 at $z = 6.229$, Isobe et al. (2023) argue it is not an AGN due to the absence of high ionization lines. It is not clear whether the enriched regions in these sources are limited to small physical regions illuminated by AGNs or spread out across the entire systems. In the case of GS_3073, the physical scale of nitrogen enhancement likely reaches the high-ionization part of the NLR but not the entire NLR according to our analyses in Section 4. This points towards an enrichment site no larger than a few hundred parsecs or even a few tens of parsecs (possible for the size of a dense NLR; Peterson et al. 2013) but not confined within the sub-parsec scale of the BLR.

The time-scale of the enrichment, on the other hand, is closely related to the rate of the occurrence of the nitrogen loudness. The resulting N/O from WR star enrichment, for example, would rapidly drop $\sim 10^{6.5}$ yr after an initial burst of star formation, which can be extended to $\sim 10^{6.9}$ yr if direct collapse of massive WR stars is considered to suppress the enrichment from CCSNe (Limongi & Chieffi 2018; Watanabe et al. 2024). Still, we note that binary evolution can further extend the WR phase (Eldridge & Stanway 2009) and its impact on the chemical enrichment remains to be investigated in chemical evolution models. The AGB enrichment, on the other hand, tends to build-up gradually $\sim 10^8$ – 10^9 yr after an initial burst of star formation, although the first AGB develops as early as 40 Myr after the onset of star formation. Due to the potential presence of the AGN continuum, the star formation history (SFH) of GS_3073 cannot be well-constrained. The only time constraint is the age of the Universe at $z = 5.55$, which is $\sim 10^9$ yr after the big bang, compatible with all aforementioned scenarios. Still, without binary evolution, the plausible timing for the enrichment scenario with WR stars might be strict in order have the WR wind enrichment while still being ahead of the subsequent CCSNe enrichment that lowers the overall N/O.

Since GS_3073 is a confirmed Type-1 AGN at a high redshift, its chemical abundance pattern might provide new clues also for the puzzling class of nitrogen-loud AGNs. It remains a matter of debate whether the nitrogen-loud quasars are overall chemically enriched with high oxygen abundances as well, or whether they are particularly enriched only in nitrogen (Jiang et al. 2008; Matsuoka et al. 2011; Araki et al. 2012; Batra & Baldwin 2014; Matsuoka et al. 2017). Similarly, whether the enrichment is limited to a small region surrounding the AGN, or rather occurs galaxy-wide, remains an open question (Collin & Zahn 1999; Baldwin et al. 2003; Wang et al. 2011; Araki et al. 2012; Cantiello et al. 2021; Huang et al. 2023). It is noteworthy that AGN activity is not necessary directly related to the nitrogen enrichment in nitrogen-loud galaxies, but it could be the key to revealing nitrogen-loud regions due to the high luminosities of AGNs (Baldwin et al. 2003).

According to the enrichment track for nitrogen-loud quasars mainly through AGB stars as adopted by Hamann & Ferland (1993), for example, a low-abundance ratio of $\log(\text{N}/\text{C}) \lesssim -1$ is generally expected at subsolar metallicities. This does not match our measurements, where $\log(\text{N}/\text{C}) \sim 0.7$ – 0.8 . Another AGB-enrichment scenario proposed by D’Antona et al. (2023) to explain the nitrogen and carbon abundances of GN-z11 is able to reach a high N/O and

a low C/O at a metallicity of $12 + \log(\text{O}/\text{H}) = 8.04$. In the scenario of D’Antona et al. (2023), ejecta from intermediate-mass AGB stars (with yields computed by Ventura et al. 2013) from a massive GC or a nuclear star cluster (NSC, which is defined as a massive, bright, and compact stellar system usually within the central 50 pc of the host galaxy; Neumayer, Seth & Böker 2020) enrich the central region of GN-z11. Meanwhile, certain dilution of the chemical abundances of the ISM through the inflow of chemically pristine gas might be needed to maintain a low metallicity. In the case of GS_3073, the abundance pattern could result from enrichment by AGB stars in an NSC with an age of $\sim 200\text{--}300$ Myr (Ventura et al. 2013; D’Antona et al. 2023). It is noteworthy that the physical sizes of NSCs are comparable with that of the enrichment site we speculated for CS_3073 and the dense environments of NSCs can potentially lead to formations of early SMBHs (Neumayer et al. 2020, and references therein).

As another possibility, the enrichment by VMSs or SMSs is also compatible with the enrichment sites of nitrogen-loud AGNs, if they are indeed spatially confined in NSCs. In the case of GS_3073, our analyses point towards a scenario where nitrogen is clearly enriched at a low oxygen abundance and the enrichment seems limited to a dense and highly ionized zone traced by rest-frame UV lines. This indicates chemical enrichment in a dense environment where stellar encounters might occur and lead to production of SMSs (Ebisuzaki et al. 2001; Portegies Zwart et al. 2004; Gieles et al. 2018). We note that the dense star-forming regions are not necessarily limited to NSCs but can arise from the self-gravitating part of the accretion discs of AGNs (e.g. Wang et al. 2011; Cantiello et al. 2021).

As speculated by the early studies of nitrogen-loud quasars, the nitrogen-loud feature might be a result of the co-evolution of AGNs and nuclear star formation (e.g. Hamann & Ferland 1993; Baldwin et al. 2003). According to this scenario, the AGN is initially highly obscured by the nuclear star formation, and the BLR only starts to be visible after the gas supply is nearly exhausted and the star formation declines. With this setup, the AGN has a higher chance to shine upon the gas recently enriched with nitrogen by NSCs and exhibit the nitrogen-loud feature. Interestingly, based on the previous observation of $[\text{C II}]\lambda 158 \mu\text{m}$ of GS_3073 in the ALMA Large Program to Investigate C+ at Early Times survey (ALPINE; Le Fèvre et al. 2020), Dessauges-Zavadsky et al. (2020) inferred a potentially low molecular gas mass fraction of $f_{\text{molgas}} \equiv M_{\text{molgas}}/(M_{\text{molgas}} + M_*) = 0.10^{+0.13}_{-0.06}$. This indicates a significant reduction of the cold gas through rapid star formation or AGN feedback. In the early Universe, with the star formation becomes more bursty and compact, the resulting ionization might play an important role in the nuclear region as well. This might explain the seemingly more frequent discoveries of nitrogen-loud galaxies at early times by JWST, if in these galaxies, the AGN activities and intense star formation are preferentially observed in a later phase of rapidly evolving NSCs or dense star formation environments. Still, we caution that the conversion from the luminosity of $[\text{C II}]\lambda 158 \mu\text{m}$ to the mass of the molecular gas has various uncertainties including the dependence on the metallicity (Zanella et al. 2018). Finally, it is worth noting that according to Schaerer et al. (2024), most of the nitrogen enhanced galaxies confirmed by JWST thus far are relatively compact and likely have dense SF environments.

5.1.2 Enrichment of iron

An additional constraint on the enrichment mechanism comes from the abundance of iron. The typical enrichment channel for Fe is by the

ejecta of Type-Ia supernovae, which has a delay time of $\sim 10^{8.5}\text{--}10^9$ yr, compatible with the age of the Universe at $z = 5.55$, although prompt production channels as short as a few 10 Myr have been suggested (Matteucci et al. 2006). The iron abundance of GS_3073 is relatively uncertain, as discussed in Section 4.6, especially given the potential presence of regions with different densities and chemical enrichment. While the most plausible range of the gas-phase Fe/O as constrained by high ionization lines including $[\text{Fe VII}]$ and $[\text{Fe IV}]$ is consistent with those of local stars and metal-poor galaxies, if Fe and O has been depleted on to dust grains, the intrinsic Fe/O can be significantly higher.

If GS_3073 has an intrinsically low Fe/O, it would be consistent with the scenario where the Type-Ia supernova enrichment has not made a significant contribution to the overall enrichment, similar to the local metal-poor galaxies. Compared to, for example, the CCSNe enrichment models computed by Watanabe et al. (2024) with yields based on Nomoto et al. (2013), $[\text{Fe}/\text{O}] \approx -0.5$ can be achieved with enrichment purely from CCSNe. As a result, there would be not enough time for significant nitrogen and carbon enrichment through the normal AGB enrichment unless the time is exactly between the plausible delay times of the AGB enrichment and the Type-Ia supernova enrichment. On the other hand, if GS_3073 has an intrinsic Fe/O value of near-solar or even super-solar at a metallicity as low as $12 + \log(\text{O}/\text{H}) \sim 8.0$, one would need an enrichment history that does not over-enrich oxygen. This again requires the suppression of CCSNe enrichment from previous star formation. Alternatively, the overabundance of Fe can be produced by the enrichment of metal-poor hypernovae (HNe). As shown by Watanabe et al. (2024), enrichment by HNe from massive stars alone at ~ 20 per cent solar abundances (corresponding to $12 + \log(\text{O}/\text{H}) \sim 8.0$) are able to produced near-solar Fe/O and Ne/O, and a slightly super-solar Fe/Ne.

In the local Universe, super-solar iron abundances up to $\text{Fe}/\text{Fe}_\odot \sim 5$ were often found in the accretion discs of AGNs based on X-ray observations (e.g. Jiang et al. 2019). Super-solar abundance ratios of Fe/O have also been found in some local extremely metal-poor galaxies (EMPGs), which, however, have low-abundance ratios of N/O at the same time (Kojima et al. 2021). According to Kojima et al. (2021) and Isobe et al. (2022), the preferred enrichment mechanism for the high Fe/O in EMPGs is by NHe and/or CCSNe from VMSs with stellar masses of $M_* \gtrsim 30\text{--}300 M_\odot$, which can potentially form by the infall of pristine gas or mergers of stars in dense star clusters. If the enrichment of Fe occurred before the enrichment of N, it could also enhance the strength of stellar winds that carry N (Vink 2023).

Combining the constraints from abundance ratios of N/O, C/O, and Fe/O, the enrichment can be driven by intermediate-mass AGB stars, VMSs/SMSs, or classical WR stars in the NSC of GS_3073 combined with CCSNe (Fe-poor), or Type-Ia supernovae or HNe (Fe-rich).

5.2 A stratified galaxy

An interesting characteristic of GS_3073 is the different gas-phase properties inferred from different sets of emission lines.

First of all, the electron densities inferred from the narrow lines of $[\text{S II}]\lambda\lambda 6716, 6731$, $[\text{Ar IV}]\lambda\lambda 4711, 4740$, and $\text{N IV}]\lambda\lambda 1483, 1486$ increase from $\sim 10^3 \text{ cm}^{-3}$ to $\sim 10^5 \text{ cm}^{-3}$. For Ar and S, Ar^{2+} has a much higher ionization potential compared to S^0 and $[\text{Ar IV}]\lambda\lambda 4711, 4740$ is more sensitive to the density at the high-density regime. Meanwhile, there is evidence in local H II regions that $[\text{S II}]\lambda\lambda 6716, 6731$ is biased towards low density regions (Méndez-Delgado et al. 2023). For N, while the ionization potential of N^{2+}

is only slightly higher than Ar^{2+} , the higher critical density of $\text{N IV}] \lambda\lambda 1483, 1486$ makes it more likely to arise from a denser region when there is density stratification. A similar high density from $\text{N IV}] \lambda\lambda 1483, 1486$ has also been reported for the nitrogen-rich galaxy at $z = 6.106$ by Topping et al. (2024). In the local nitrogen enhanced galaxy Mrk 996, James et al. (2009) found a density stratification where the high density gas reaches a density of $\log(n_e) = 7.25^{+1.25}_{-0.75} \text{ cm}^{-3}$ and is nitrogen enhanced. The low density gas has $n_e \approx 10\text{--}170 \text{ cm}^{-3}$ is nitrogen-normal compared to local galaxies. In another higher redshift and lensed galaxy, the Sunburst Arc at $z = 2.37$, Pascale et al. (2023) found evidence for high-pressure, high-density, and nitrogen enhanced clouds surrounding a young super star cluster. The high-density clouds have densities of $n_e \sim 10^5 \text{ cm}^{-3}$ and are likely surrounded by more extended low-density and nitrogen-normal clouds with densities of $n_e \sim 10^3\text{--}10^4 \text{ cm}^{-3}$. Finally, it is noteworthy that we only used the narrow component of $\text{N IV}] \lambda\lambda 1483, 1486$, meaning the density stratification is within the NLR. The density stratification of NLRs has already been noted in previous observations of AGNs (e.g. Binette & Rodríguez-Ardila 1999).

An even more interesting type of stratification in the NLR of GS_3073 is the ionization stratification. The ICF for oxygen as inferred from the optical He II and He I lines implies an ionization state where most oxygen is in O^{2+} . However, the ionization condition for UV lines is clearly different. The presence of strong $\text{N IV}]$ and N V lines as well as the evidence of O VI in the Lyman continuum regime requires a non-negligible amount of high ionization species. Based on the ionic species of UV lines, we inferred there is likely more than 1/4 of oxygen in ionization stages higher than O^{2+} within the UV-line dominated zone. This result suggests the UV-line dominated zone is not only denser but also more highly ionized. Besides these UV lines, there is also potential detection of optical coronal lines that have ionization potentials $\gtrsim 100 \text{ eV}$, which likely arise from an even more central and highly ionized zone (Ferguson, Korista & Ferland 1997; Murayama & Taniguchi 1998; Rose et al. 2015).

The potential presence of $[\text{Fe VII}] \lambda 6087$ and $[\text{Fe XIV}] \lambda 5303$, if confirmed, might suggest little Fe depletion in the coronal-line region (Nagao et al. 2003; McKaig et al. 2024). Meanwhile, dust attenuation is clearly present given the observed He II UV-to-optical ratio. While it remains unclear how much dust depletion would be sufficient to produce the moderate amount of attenuation we observed, these results point to a possibility that the dust distribution is also stratified. In such a scenario, dust grains are destroyed in the coronal-line region by the intense radiation field, but survive in less ionized and outer zones. While the stratification of dust distribution has long been considered as part of the standard AGN models, the exact location at which dust starts to emerge is debatable (e.g. Shields, Ludwig & Salvander 2010). For GS_3073, our measurements indicate the destruction of dust beyond the BLR into the NLR, where forbidden lines with high critical densities can still arise. This is consistent with the result of Nagao, Maiolino & Marconi (2006b), where the line ratios from the high-ionization part of the NLRs in a sample of X-ray selected intermediate-redshift AGNs are more aligned with predictions from dust-free photoionization models.

Finally, perhaps the most intriguing type of stratification we found in GS_3073 is the chemical abundance stratification, as also found by James et al. (2009) and Pascale et al. (2023) in Mrk 996 and the Sunburst Arc, respectively. The abundance ratio of N/O inferred from the low-critical density and low-ionization lines including $[\text{O II}]$ and $[\text{N II}]$ in the PRISM and G395H spectra appears only slightly higher than the N/O of local galaxies with similar metallicities. In contrast, the N/O inferred from the high-critical density and high-ionization

UV lines is significantly higher than local galaxies, and also the highest among the nitrogen-loud galaxies confirmed by JWST, as shown in Fig. 4. While the potential outflow component in the optical lines and the blending of He II and $[\text{O III}]$ could bring the N/O ratios estimated from the two sets of lines closer, the lower limit on the UV N/O is still significantly higher than the highest N/O we estimated from $[\text{N II}]/[\text{O II}]$. This result suggests the nitrogen is more enriched in the UV-line dominated zone, which is a denser and more highly ionized zone compared to the low-density and low-ionization zone where lines such as $[\text{O II}]$ and $[\text{N II}]$ originate in. Presumably, the UV-line dominated zone lies closer to the accretion disc of the central SMBH and thus is more directly affected by the abundance pattern potentially resulting from dense nuclear star formation. This would then suggest the nitrogen-loudness is confined to the BLR and the inner NLR and would reduce the total mass of stars required to build the observed abundances. Still, with the current observations, we cannot constrain precisely the physical scale of the enriched region.

Also, it is possible that the optical narrow lines are contaminated by SF regions in GS_3073. The narrow optical line ratios of GS_3073, as shown by Übler et al. (2023), lies close to the boundary of SF regions and AGN regions in the BPT diagram. While this behaviour can be simply explained by a metal-poor NLR (Scholtz et al. 2023), we cannot fully rule out the contribution from metal-poor SF regions. If the peculiar enrichment of nitrogen in GS_3073 is confined to the nuclear region as we speculated, then the non-nuclear region in GS_3073 can simply show ‘normal’ abundances. As a result, the contamination from non-nuclear region for optical lines would lead to an estimation of a less extreme N/O.

In summary, we found evidence for stratification in the abundance pattern of nitrogen in GS_3073, which appears to correlate with the stratification in the electron density and the ionization state of the gas. We thereby speculate that the enrichment is confined to the dense and highly ionized central region of GS_3073. Our results suggest that the nitrogen abundance is enriched locally but at a scale larger than the BLR as traced by the highly ionized part of the NLR. This is consistent with the enrichment by NSCs we discussed in the last section.

6 CONCLUSIONS

In this work, we investigated the chemical abundance pattern of GS_3073, a galaxy at $z = 5.55$, hosting a Type-1.8 AGN, by using JWST/NIRSpec IFS observations and VLT/VIMOS data. The presence of an AGN illuminating the gas in the nuclear region and the rest of the galaxy, combined with the sensitivity of JWST-NIRSpec and VLT-VIMOS, allows the detection of about 40 emission lines in the rest-frame UV and optical wavelength range, hence enabling an unprecedented investigation in terms of chemical enrichment and physical properties of the gas.

We summarize our findings in the following.

- (i) The flux ratios between the (semiforbidden) rest-frame UV emission lines of GS_3073 imply an ionization condition consistent with the inner region of the galaxy (inner part of the narrow line region, or a combination of an NLR and a BLR), characterized by high densities of $n_e \sim 10^5 \text{ cm}^{-3}$ and with an ionization parameter of $\log U \sim -1.5 \text{--} -2$. This is consistent with the interpretations based on the rest-frame optical permitted lines, where hydrogen Balmer lines and helium lines show both narrow and broad components.
- (ii) The rest-frame UV emission-line flux ratios of GS_3073 indicate that, in such dense gas, nitrogen is highly enriched with

respect to oxygen (N/O about 20 times higher than solar), carbon is not as enriched as nitrogen (C/O about solar or slightly subsolar), and Fe/O is subsolar. In particular, the relative abundance of nitrogen is clearly above the N/O versus O/H relation observed in low-redshift galaxies. The N/O and C/O abundance patterns of GS_3073 are similar to those of nitrogen-loud quasars at low redshifts as well as several nitrogen-loud galaxies recently revealed by JWST, and GS_3073 is actually among the most nitrogen-rich of them all. Therefore, with its ~ 40 lines detected, this system provides an excellent test bench for investigating nitrogen-enriched systems in the early Universe. In particular, the constraints on the iron abundance provide new insights to be compared with chemical evolution models.

(iii) The abundance ratio of N/O inferred from the rest-frame optical *forbidden* emission lines, including [N II] and [O II] (tracing much lower gas densities), is significantly lower than that inferred from the rest-frame UV (semi-forbidden) emission lines. We interpret this difference as an indication of a stratification in the chemical abundances, where the inner, denser, and more highly ionized region of the galaxy is more chemically enriched. The chemical stratification is associated with an ionization stratification and a density stratification, where the UV lines generally show higher ionization states and a higher electron density compared to the low-ionization and low-critical density optical emission lines. Importantly, the extreme nitrogen enrichment is confined to the central, high-density region, not to the bulk of the host galaxy.

(iv) While the flux ratio between the UV and optical He II lines is consistent with a moderate amount of dust attenuation with $A_V \sim 0.39-0.49$, the potential detection of the coronal line [Fe VII] $\lambda 6087$ indicates destruction of dust grains in the inner part of the galaxy, likely due to the strong AGN radiation field.

(v) The chemical abundance pattern of GS_3073 can be explained by a variety of enrichment mechanisms. It is possible to reproduce the observed N/O and C/O with enrichment by AGB ejecta, winds from very massive stars (VMSs), supermassive stars (SMSs), or classical WR stars in a dense nuclear star cluster (NSC). To reproduce the observed Fe/Ne and Ne/O abundance ratios, enrichment by a combination of core collapse SNe and Type-Ia supernovae, or hypernovae is plausible.

(vi) Given the observed stratification in the density, ionization state, and chemical abundances, we speculate the extreme enrichment pattern seen in GS_3073 preferentially occurred in a dense NSC, meaning the enrichment is spatially confined within the central few parsecs. Such an environment would also allow production of VMSs and SMSs through frequent stellar encounters.

(vii) The potential lack of molecular gas in GS_3073 suggests it might have reached a later stage of star formation due to the consumption of gas and feedback. Therefore, the reason that GS_3073 shows nitrogen-loudness might be similar to the AGN-SF co-evolution scenario proposed for nitrogen-loud quasars, where the AGN becomes less obscured but still active close to the end of a rapid star formation in a dense nuclear environment.

As star formation becomes more bursty and intense in the metal-poor and dense environments in the early Universe, the chance of observing galaxies in the nitrogen-loud phase of their chemical evolution might increase. This potentially explains the discoveries of several nitrogen-loud galaxies by JWST, as well as the fact that not all of them exhibit clear evidence for AGN activity, although AGN illumination of the central, dense region facilitates their discovery. With the currently observed number of early galaxies increasing thanks to JWST, we might start to be able to study the statistical behavior of nitrogen enrichment at high redshifts. The statistical analyses on the

chemical abundance patterns would be vital for understanding the general enrichment channel at early times. In addition, as already noted by many current studies, new methods for distinguishing AGN ionization from SF ionization at high redshifts are urgently needed. This would help us understand how the (peculiar) abundance patterns might be associated with AGN or SF activities and further test previous theories for chemical enrichment of quasars and dense star clusters. Finally, how the metals are distributed differently in the early galaxies remain poorly constrained in observations. The chemical stratification in GS_3073 implies that the early enrichment in galaxies may be highly inhomogeneous. Future explorations of deep IFS data of high- z galaxies will be useful for understanding the differential enrichment of metals in young galaxies in the early Universe.

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DATA AVAILABILITY

The JWST/NIRSpec IFS data used in this paper are available through the MAST portal. The VLT/VIMOS data used in this paper are available from the ESO Phase 3 Archive. All analysis results of this paper will be shared on reasonable request to the corresponding author.

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APPENDIX A: JWST/NIRCAM IMAGING OF GS_3073

In this Appendix, we present JWST/NIRCam images of GS_3073, obtained as part the JWST Advanced Deep Extragalactic Survey (JADES; Eisenstein et al. 2023), and publicly available as part of the JADES data release 1 (Rieke et al. 2023). In addition to the continuum, the different filters capture nebular line emission from N v ($F090W$), He II–C III] ($F115W$) and [O III] ($F356W$); Ly α and C IV fall under the low-sensitivity region of $F090W$ and $F115W$, respectively. $F150W$ and $F200W$ probe mostly the rest-UV continuum, without high equivalent-width line emission. Fig. A1 show the colour-composite images constructed from the above bands.

The images show two distinct sources in addition to GS_3073, as reported by Übler et al. (2023) based on NIRSpec PRISM data. Leveraging the superior spatial resolution of NIRCam at 0.9–1.5 μm , we can clearly resolve the east and north-west sources as being spatially separated from GS_3073. From the middle panel of Fig. A1, one can see a 0.3 arcsec-extraction aperture as we adopted for our fiducial measurements would avoid light contamination from the two additional sources. In comparison, a 1 arcsec-extraction aperture as adopted for generating an alternative PRISM spectrum as well as a 1 arcsec-slit used for extracting the VIMOS spectrum

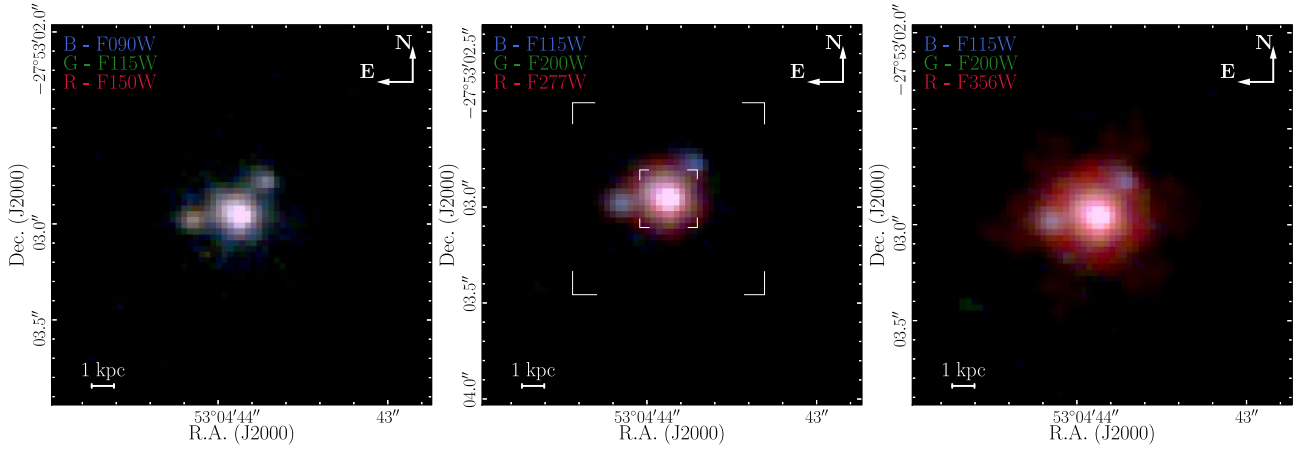


Figure A1. Wide-band colour-composite images constructed from JWST/NIRCam observations of GS_3073 (Rieke et al. 2023). In the middle panel, we show also the 0.3 arcsec-aperture and the 1 arcsec-aperture we used for extracting NIRSpec/PRISM IFU data.

would include the two additional sources. We note that neither source displays an excess in $F356W-F277W$ or $F410M-F444W$, implying weak line emission in these bands. Both sources are undetected in HST/ACS $F435W$ and $F606W$, consistent with $z > 5$. Both sources appear significantly bluer in colour than GS_3073, which could indicate either bright nebular emission in $F090W$ and $F115W$, or a steep continuum. To further understand the potential contamination from these sources in the 1 arcsec-spectra, we extract a $0.1 \text{ arcsec} \times 0.1 \text{ arcsec}$ box centering at each source in the PRISM IFU data. We found that the integrated light centering at the source to the east of GS_3073 contributes an $[\text{O III}]\lambda 5007$ flux roughly 10 per cent of that from the central 0.3 arcsec-extraction, and an $\text{N IV}]\lambda 1483, 1486$ flux less than 5 per cent of that from the central 0.3 arcsec-extraction. In comparison, the integrated light centering at the source to the northwest of GS_3073 contributes an $[\text{O III}]\lambda 5007$ flux roughly 1 per cent of that from the central 0.3 arcsec-extraction, and an $\text{N IV}]\lambda 1483, 1486$ flux up to 1 per cent of that from the central 0.3 arcsec-extraction. In conclusion, these additional sources unlikely contaminate the nebular emission of the central source significantly and we emphasize that our main conclusions are based on the central 0.3 arcsec-extraction with little contamination.

Assuming both sources to be at the same redshift as GS_3073, they could be interpreted as low-mass satellites dominated by blue stellar populations. Intriguingly, similar sources are found near other broad-line AGN at redshifts $z \sim 5$ (Maiolino et al. 2024c; Matthee et al. 2024), suggesting a possible connection between strong AGN activity and minor mergers.

APPENDIX B: NEBULAR ATTENUATION CURVE

In Section 4.1, we have discussed the dust attenuation probed by He II line ratios and the hydrogen Balmer lines, where the attenuation curve is assumed to follow the shape of an average SMC extinction curve (Gordon et al. 2003). In this Appendix, we investigate the shape of the attenuation curve in greater detail.

Figs B1 and B2 show comparisons between the predicted line ratios from some of the extinction curves in the literature and those measured from the NIRSpec spectra of GS_3073. All line ratios are normalized by the Case B values from Draine (2011). The

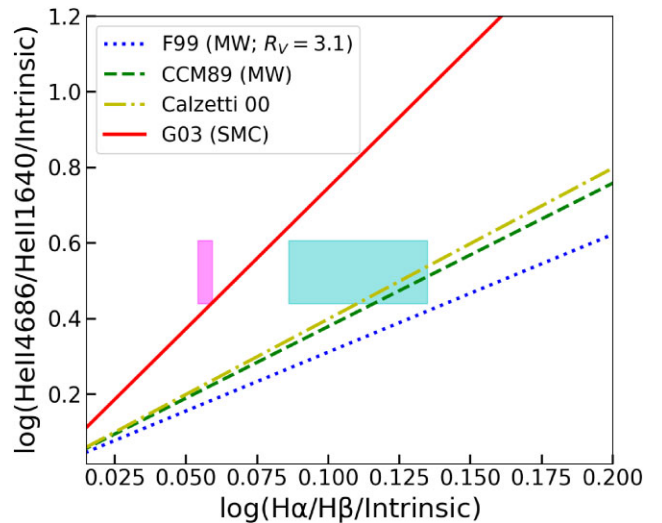


Figure B1. Diagnostic diagram constraining the shape of the UV-to-optical attenuation curve. The lines displayed correspond to the predicted He II flux ratio versus the Balmer decrement for extinction curves from Cardelli et al. (1989), Fitzpatrick (1999), Calzetti et al. (2000), and Gordon et al. (2003). The magenta shaded region close to the SMC extinction curve corresponds to the plausible range of line ratios measured from the 0.3 arcsec-PRISM spectrum. For the cyan shaded region close to the MW extinction curves, we replace the Balmer decrement with that of the broad component measured in the R2700 spectrum by Übler et al. (2023).

total line flux ratios measured from the PRISM spectrum prefers steep attenuation in the UV closer to the predictions by the SMC curve. If we replace the Balmer decrement with the value measured from the broad lines in the R2700 NIRSpec/grating spectrum, the observed line ratios move closer to the predictions by the curve from either Cardelli, Clayton & Mathis (1989) or Calzetti et al. (2000). The caveat, however, is that we cannot compare it with the flux ratio from the broad He II lines since they are not resolved in PRISM. Also, it is likely that the BLR is more obscured and thus the shape of the attenuation curve for the broad lines is also close to that of the SMC extinction curve. For the optical part, the left panel of Fig. B2 suggests it is close to the MW extinction curve from Fitzpatrick (1999), although being slightly steeper redwards

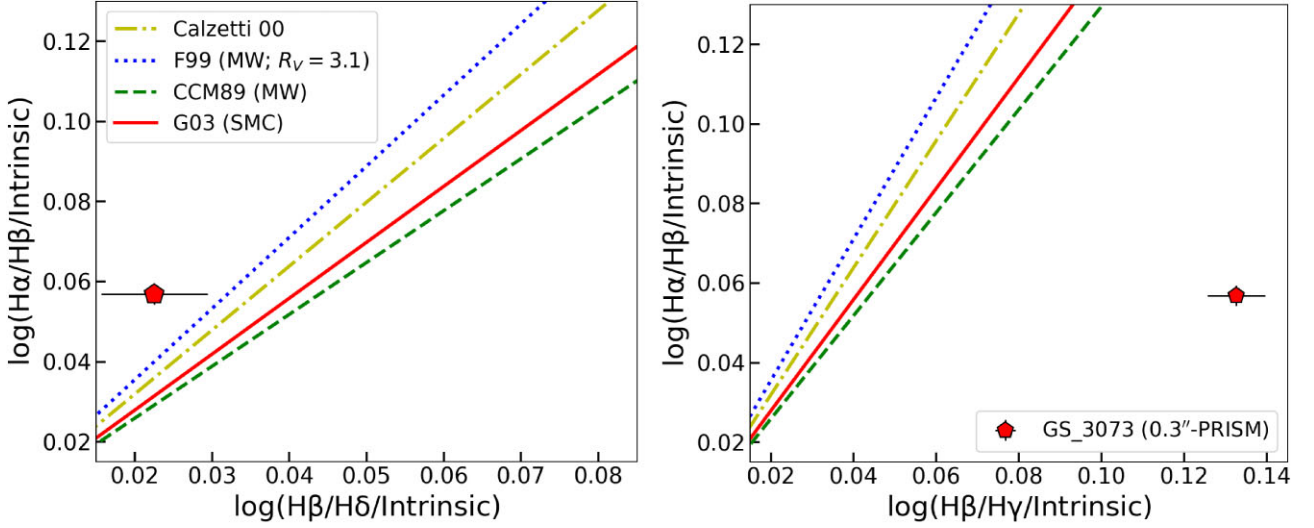


Figure B2. Diagnostic diagrams constraining the shape of optical attenuation curve. The extinction curves are the same as the ones shown in Fig. B1. The pentagons represent the values we measured from the 0.3 arcsec-PRISM spectrum.

to $H\beta$. However, from Fig. B2, it appears $H\gamma$ is more attenuated compared to $H\delta$. We caution that the attenuation from $H\gamma$ is potentially affected by blending with $[\text{O III}]\lambda 4363$ in the PRISM spectrum¹⁴ (e.g. an ~ 20 per cent underestimation for $H\gamma$ would make $H\beta/H\gamma$ roughly consistent with the attenuation curves shown in Fig. B2).

Although in the main text we have assumed the SMC extinction curve when dereddening for example $[\text{N II}]/[\text{O II}]$, assuming other extinction curves only change the correction by 0.02 dex at most. In most cases, the SMC correction in the optical regime serves as an upper limit. When using $[\text{N II}]/[\text{O II}]$, we also considered the case where there is no extinction for these narrow lines, thereby including various possibilities. Again, we would like to point out the spatial distribution of dust in GS_3073 is likely complex, with the nuclear region being more obscured. This is supported by the significantly different Balmer decrements from broad emission lines and narrow emission lines in the R2700 NIRSpc/grating spectrum by Übler et al. (2023). We will explore more systematically shapes of the attenuation curves in JWST identified type-1 AGN in future work.

APPENDIX C: COMPARISONS WITH ADDITIONAL PHOTOIONIZATION MODELS

In Section 4, we have compared the measured line ratios of GS_3073 with a fiducial set of photoionization models. Here, we show further comparisons with models under different assumptions.

In Fig. C1, we show two additional NLR models. Different from our fiducial NLR model, these new models have their incident SEDs generated by the analytical AGN SED described in Pezzulli et al. (2017), which is a function of the black hole mass and the Eddington ratio. We considered two SEDs with a black hole mass of $M_{\text{BH}} = 10^8 M_{\odot}$ and Eddington ratios of $\lambda_{\text{Edd}} = 0.1$ and 1, matching the range of parameters estimated by Übler et al. (2023) for GS_3073. We set the rest of the model parameters the same as those in the fiducial model.

Overall these additional models do not change our conclusions. The measured nebular line ratios are still more consistent with ionization by the AGN continuum emission, although the best-fitting ionization parameter becomes $\log U \approx -1.5 \sim -1$. From the right panel of Fig. C1, one can see the gas-phase N/O indicated by the NLR models is still roughly 0.43 dex.

¹⁴We note that in the main text, we did not use $[\text{O III}]\lambda 4363$ measured in PRISM during our analyses but took the value measured in G395H.

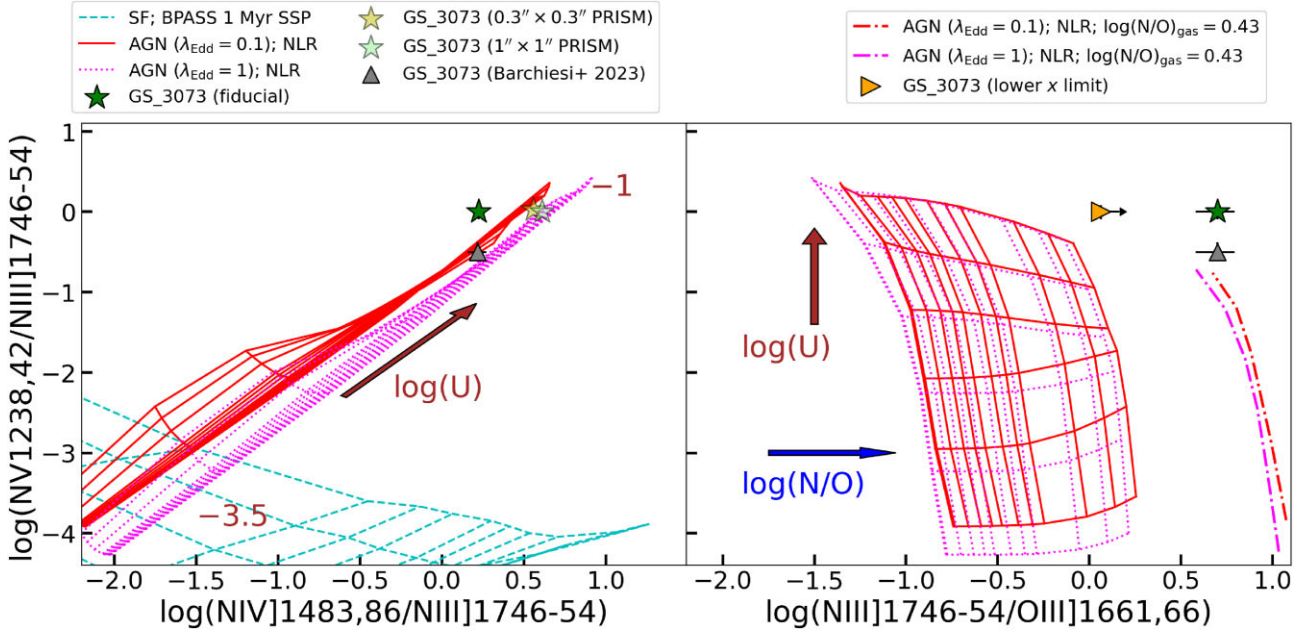


Figure C1. Comparisons between observed line ratios of GS_3073 and those predicted by two additional AGN NLR models. These new models assuming a functional form of the SED parametrized by the black hole mass and the Eddington ratio as adopted by Pezzulli et al. (2017).

APPENDIX D: GAS-PHASE FE/O BASED ON $[\text{O III}]/[\text{Fe IV}]$

In the main text, we used the upper limit on the flux ratio of $[\text{Ne V}]/[\text{Fe VII}]$ to constrain the gas-phase abundance of Fe. In this Appendix, we investigate the Fe abundance constrained by the flux ratio of $[\text{O III}]\lambda 5007/[\text{Fe IV}]\lambda\lambda 2829, 2835$. In Fig. D1, we compare the measured $[\text{O III}]\lambda 5007/[\text{Fe IV}]\lambda\lambda 2829, 2835$ versus $\text{N V}\lambda\lambda 1238, 1242/\text{N IV}\lambda\lambda 1483, 1486$ from the 0.3 arcsec-PRISM spectrum of GS_3073 to those predicted by photoionization models for NLRs of AGN. We have corrected the flux ratio of $[\text{O III}]\lambda 5007/[\text{Fe IV}]\lambda\lambda 2829, 2835$ for dust attenuation assuming $A_V = 0.44$ and using the SMC extinction curve (see Section 4.1). The photoionization models have the same parameters as those in Fig. 9. Specifically, the hydrogen density is assumed to be $n_H = 5 \times 10^5 \text{ cm}^{-3}$, the oxygen abundance is set to 20 per cent solar (although the nitrogen and carbon abundances are not relevant here, they are set to follow the constraints in Figs 5 and 7), neither dust nor dust depletion is included, the ionization parameter is varied in a range of $-3.5 \leq \log(U) \leq -1$, and the Fe abundance is varied in a range of $-0.6 \leq [\text{Fe}/\text{H}] \leq 0$.

From Fig. D1, the best matched Fe abundance is roughly 0.5–0.6 dex below solar, consistent with the lower limits constrained by $[\text{Ne V}]/[\text{Fe VII}]$, which ranges from 0.6 dex below solar to solar. If Fe is depleted onto dust grains in the $[\text{Fe IV}]$ emitting region, the intrinsic Fe abundance should be higher. Regardless, as mentioned

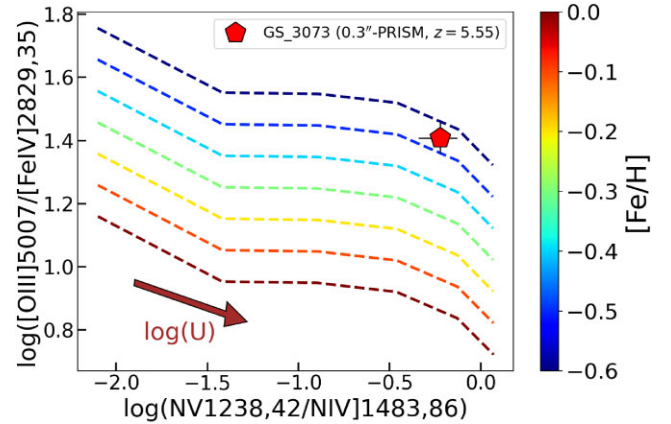


Figure D1. Diagnostic diagram composed of $\text{N V}/\text{N IV}$ and $[\text{O III}]/[\text{Fe IV}]$. The dashed coloured lines are photoionization models with parameters similar to the NLR models shown in Fig. 9, having different Fe abundances in a range of $-0.6 \leq [\text{Fe}/\text{H}] \leq 0$ from top to bottom, where $[\text{Fe}/\text{H}] \equiv \log(\text{Fe}/\text{H}) - \log(\text{Fe}/\text{H})_\odot$.

in the main text, one needs to be cautious about this simple model-based derivation given the very different critical densities of $[\text{Fe IV}]$ and $[\text{O III}]$.

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