

A Fleeting GLIMPSE of N/O Enrichment at Cosmic Dawn: Evidence for Wolf Rayet N Stars in a $z = 6.1$ Galaxy

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ABSTRACT

We present the discovery of extreme nitrogen enrichment by Wolf Rayet nitrogen stars (WN) in the metal-poor ($\sim 10\%Z_{\odot}$), lensed, compact ($R_{\text{eff}} \sim 20$ pc) galaxy RXCJ2248 at $z = 6.1$, revealed by unprecedentedly deep JWST/NIRSpec medium-resolution spectroscopy from the GLIMPSE-D Survey. The exquisite S/N reveals multiple high-ionization nebular lines and broad Balmer and [O III] components ($\text{FWHM} \sim 700 - 3000 \text{ km s}^{-1}$). We detect broadened He II $\lambda 1640$ and $\lambda 4687$ ($\text{FWHM} \sim 530 \text{ km s}^{-1}$) and strong N III] $\lambda 4642$ emission consistent with a population of WN stars, making RXCJ2248 the most distant galaxy with confirmed WR features to date. We measure the multi-phase nebular density across five ions, the direct-method metallicity ($12 + \log(\text{O}/\text{H}) = 7.749 \pm 0.023$), and a non-uniform elemental enrichment pattern of extreme N/O enhancement ($\log(\text{N}/\text{O}) = -0.390 \pm 0.035$ from N^+ , N^{+2} , and N^{+3}) and suppressed C/O relative to empirical C/N trends. We show that this abundance pattern can be explained by enrichment from a dual-burst with a low WC/WN ratio, as expected at low metallicities. Crucially, these signatures can only arise during a brief, rare evolutionary window shortly after a burst ($\sim 3 - 6 \text{ Myr}$), when WN stars dominate chemical feedback but before dilution by later yields (e.g., supernovae). The observed frequency of strong N emitters at high- z implies a $\sim 50 \text{ Myr}$ burst duty cycle, suggesting that N/O outliers may represent a brief but ubiquitous phase in the evolution of highly star-forming early galaxies. The detection in RXCJ2248, therefore, provides the first direct evidence of WN-driven chemical enrichment in the early Universe and a novel timing argument for the bursty star formation cycles that shaped galaxies at cosmic dawn.

Keywords: Chemical abundances (224), H II regions (694), Interstellar medium (847), Interstellar line emission (844), High-redshift galaxies (734), Star-forming galaxies (1560), Galaxy chemical evolution (580)

1. INTRODUCTION

A key tracer of galaxy evolution is the change in their chemical composition over time. The metallicity of a galaxy is a sensitive observational diagnostic of its past star forma-

tion history and present-day evolutionary state as metallicity increases with each successive generation of massive star (MS) yields (e.g., Tosi 1988; Roy & Kunth 1995; Berg et al. 2019; Maiolino & Mannucci 2019). Oxygen is an important tracer of metallicity because it is the most abundant element

in the Universe after H and He and is convenient to observe, with ubiquitous emission lines from H II regions in the rest-frame optical regime. While O emission in dwarf and spiral galaxies has been widely observed in the rest-frame optical and UV (e.g., Kennicutt 1992; Izotov & Thuan 1999; van Zee & Haynes 2006; Berg et al. 2012; Berg et al. 2016; Senchyna et al. 2017; Berg et al. 2019; Rogers et al. 2022), the N emission in these same galaxies has been predominantly traced only in the optical through the low-ionization [N II] $\lambda\lambda 6550, 6585$ emission lines. In general, there is a surprising dearth of detections of the high-ionization N emission counterparts in local galaxies, totaling less than 10 galaxies with significant detections of either N IV] $\lambda\lambda 1483, 1486$ or N III] $\lambda 1750$ (e.g., Mingozi et al. 2022; Martinez et al. 2025). However, with the advent of JWST, there is a growing prevalence of high-redshift ($z \gtrsim 5$) galaxies with extreme properties, including intense UV N emission (e.g., Bunker et al. 2023; Isobe et al. 2023; Castellano et al. 2024; Ji et al. 2024; Schaerer et al. 2024; Marques-Chaves et al. 2024; Harikane et al. 2025a; Hsiao et al. 2024; Naidu et al. 2025; Topping et al. 2025b).

The first noted, and one of the most distant, examples of extreme rest-frame UV N emission comes from the spectroscopically-confirmed $z = 10.6$ galaxy, GN-z11. JWST spectra of GN-z11 revealed surprisingly strong N IV] $\lambda\lambda 1483, 1486$ and N III] $\lambda 1750$ emission (e.g., Bunker et al. 2023) that corresponds to super-solar N/O enrichment ($\log(\text{N}/\text{O}) > -0.25$; e.g., Cameron et al. 2023). Subsequently, enhanced N/O has been reported in a number of high- z galaxies, including GDS 3073 ($z = 5.55$; Ji et al. 2024), RXCJ2248-ID ($z = 6.10$; Topping et al. 2024), A1703-zd6 ($z = 7.04$; Topping et al. 2025b), CEERS-1019 ($z = 8.68$; Marques-Chaves et al. 2024), GNz9p4 ($z = 9.38$; Schaerer et al. 2024), GHZ9 ($z = 10.15$; Napolitano et al. 2024), GHZ2 ($z = 12.34$; Castellano et al. 2024), and MoM-z14 ($z = 14.44$; Naidu et al. 2025). For a review of nitrogen line detections, see Stark et al. (2025). Such strong nebular N^{+3} emission requires a relatively hard ionizing radiation field ($\gtrsim 47.4$ eV), where models of massive stars predict few photons. On the other hand, N^{+2} has a lower ionization potential (~ 29.6 eV), but statistically significant detections are strikingly rare in integrated galaxy spectra (e.g., Berg et al. 2018; Mingozi et al. 2022; Bunker et al. 2023) and are only expected to be strong at the highest possible nebular temperatures ($\sim 2.5 \times 10^4$ K). Further, the timing of the incredibly high N/O abundances reported for the high- z UV N emitters just a few 100 Myr after the Big Bang is surprising. Such rapid N enrichment so early in the universe challenges our understanding of galaxy formation and chemical evolution.

The discovery of a significant nitrogen enhancement shortly after the Big Bang was surprising because it contradicts our longstanding understanding of N production. In

typical chemical evolution modeling, some nitrogen enrichment can occur early on via core collapse supernova, but substantial nitrogen enrichment only occurs 100s of Myr after the onset of star formation via asymptotic giant branch (AGB) stars (e.g., Vincenzo et al. 2019; Kobayashi et al. 2020). Thus, alternative, faster enrichment methods are needed to explain substantial nitrogen enrichment in early galaxies. As a result, the necessary ionizing flux and conditions to produce the unexpectedly strong N^{+3} and N^{+2} emission observed in high-redshift galaxies have been attributed to more extreme sources such as active galactic nuclei (AGN; Maiolino et al. 2023), Wolf Rayet stars (WR; e.g., Senchyna et al. 2023; Watanabe et al. 2024; Gunawardhana et al. 2025), globular cluster precursors (e.g., Charbonnel et al. 2023; Ji et al. 2025), super star clusters (e.g., Pascale et al. 2023), very massive stars ($M_* > 10^2 M_\odot$; e.g., Vink 2023), or super massive stars ($M_* > 10^3 M_\odot$; e.g., Charbonnel et al. 2023; Nagele & Umeda 2023), tidal disruption events (e.g., Cameron et al. 2023; Watanabe et al. 2024), and more.

Here we investigate the $z = 6.1$ lensed galaxy RXCJ2248-ID3. RXCJ2248-ID was first identified by Boone et al. (2013), Balestra et al. (2013), and Monna et al. (2014) and discovered to be a high-ionization, compact, metal-poor, N-enhanced galaxy by Mainali et al. (2017), Schmidt et al. (2017), and Topping et al. (2024). We present extremely deep JWST/NIRSpec observations of RXCJ2248-ID3 that provide the first direct evidence confirming N-type WR stars as the physical mechanism driving its extreme nitrogen enrichment (Topping et al. 2024). The remainder of this paper is organized as follows. The observations and data reduction are briefly described in Section 2.1, followed by a description of the emission line fits, including the broad lines related to the WR feedback, in Section 2.2. We present the discovery of Wolf Rayet nitrogen stars at high-redshift via their spectral signatures in Section 3. We determine new nebular properties and nitrogen abundances in Section 4 and compare them to populations of both low- and high-redshift galaxies. We discuss the source of N enrichment in the early universe and subsequently estimate mass production and timing arguments in Section 5. Finally, we present our conclusions in Section 6. Throughout this work we adopt cosmological parameters of $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.30$, and $\Omega_\Lambda = 0.7$ and the solar abundance pattern from Asplund et al. (2021).

2. JWST/NIRSPEC SPECTRA

RXCJ2248 is a galaxy at $z \sim 6.1$ that is lensed into multiple images by the Abell S1063 cluster ($\alpha = 22:48:44.13$, $\delta = -44:31:57.50$) at a redshift of $z = 0.348$. We present an analysis of the brightest image, RXCJ2248-ID3 ($J = 25.0$), which has a magnification of $\mu \sim 7$ (Furtak et al. 2025). RXCJ2248-ID was discovered as a $z \sim 6$ candidate (Boone et al. 2013; Monna et al. 2014) using the 16-band *HST* photometry of the

CLASH Survey and spectroscopically-confirmed via Visible Multi-Object Spectrograph (VIMOS)/VLT observations by Balestra et al. (2013). RXCJ2248-ID3 was soon found to be an exciting extreme emission line galaxy via ground-based spectroscopy (Mainali et al. 2017), with strong detections of high-ionization emission such as O III] $\lambda\lambda 1661, 1666$ and ionC4 $\lambda\lambda 1548, 1550$ but no He II, suggesting star formation as the ionizing source rather than an AGN. These spectra motivated further rest-UV+optical study with *JWST*/NIRSpec by Topping et al. (2024). This work performed direct metallicity calculations to show that RXCJ2248-ID3 is one of the most extreme N/O-enhanced ($\log(\text{N}/\text{O}) = -0.39^{+0.11}_{-0.10}$), metal-poor ($12 + \log(\text{O}/\text{H}) = 7.43^{+0.17}_{-0.09}$) galaxies, with high-ionization ($[\text{O III}] \lambda 5008/[\text{O II}] \lambda 3727 = 184$), and high nebular density ($6.4 \times 10^4 \leq n_e \text{ (cm}^{-3}\text{)} \leq 3.1 \times 10^5$). They also used spectral energy distribution (SED) fitting with a constant star formation history to characterize the low stellar mass ($M_* \sim 10^8 M_\odot$) and young-massive star population (~ 2 Myr) of RXCJ2248. Topping et al. (2024), therefore, suggest that the N/O enrichment may be due to a short-lived phase that many $z > 6$ bursty galaxies experience. In this paper, we build on the work of Topping et al. (2024) with new, extraordinarily deep rest-optical *JWST*/NIRSpec observations of RXCJ2248-ID3 from the GLIMPSE-D Survey, a Director’s Discretionary Time follow-up program described below.

2.1. Observations and Reduction

The work presented here uses both the rest-UV *JWST*/NIRSpec archival spectra from *JWST* PID 2478 and new rest-optical *JWST*/NIRSpec spectra from the GLIMPSE-D Survey. Properties of RXCJ2248-ID and observation details are presented in Table 1.

The GLIMPSE Survey is a large Cycle 2 *JWST* program (PID 3293; PIs Atek & Chisholm) that performed ultra-deep NIRCам imaging (~ 30.8 mag at 5σ over $0.8\text{--}5\mu\text{m}$) in seven broadband and two medium-band filters of the lensing cluster Abell S1063 (Atek et al. 2025). Claeysens (2025) performed size and photometric measurements of RXCJ2248-ID in the different multiple images. The SED fitting was performed with the Bayesian Analysis of Galaxies for Physical Inference and Parameter ESTimation (BAGPIPES; Carnall et al. 2018) code with “Binary Population and Spectral Synthesis” (Eldridge et al. 2017, BPASS v2.14) stellar population synthesis burst models and cloudy v23.01 photoionization models (Chatzikos et al. 2023; Gunasekera et al. 2023). Priors were used to be physically consistent with the source, i.e., high ionization parameter ($-2 \leq \log U \leq -1$), low extinction ($A_V < 0.5$ mag), low-metallicity ($Z < 0.4 Z_\odot$), and bursty star formation ($\tau = 1$ Myr, i.e., close to a single burst, or $\tau = 10$ Myr). The resulting best fit has a young age ($t_{\text{age}} = 1.6^{+11.9}_{-0.9}$ Myr) and low stellar mass of $M_* = 4.6^{+21.1}_{-2.3} \times 10^7 M_\odot$ but with in a compact size of $R_{\text{eff}} = 19.5^{+13.99}_{-4.72}$ pc such that the stellar

surface mass density of $\Sigma_* = 1.1^{+5.2}_{-0.3} \times 10^4 M_\odot \text{ pc}^{-2}$. This value is akin to the highest densities found in globular clusters, similar to the ones reported for young star clusters and clumps at high redshift (Messa et al. 2025; Claeysens et al. 2025), and broadly consistent with the conclusions presented in Topping et al. (2024).

Subsequent medium-resolution ($R \sim 1000$) spectra of RXCJ2248-ID3 were obtained as part of the follow-up GLIMPSE-D Survey: *JWST* Director’s Discretionary Time (DDT) Program 9223 (PIs Fujimoto & Naidu) targeting a Pop III candidate in Fujimoto et al. (2025) using NIRSpec Multi-Object Spectroscopy (MOS) with the G395M grating and F290LP filter. RXCJ2248-ID3 was observed for a total of 13 exposures using a 3-point nod pattern and NRSIRS2 readout, totaling ~ 30 hours of integration. The MSA slit positions covering RXCJ2248-ID3 of the three pointings are shown in Figure 1.

We augment the rest-optical GLIMPSE-D data with archival rest-far-UV G140M/F100LP and rest-near-UV G235M/F170LP observations from PID 2478 (PI Stark), covering the rest-frame $\sim 1400\text{--}4000 \text{ \AA}$ range. This program also observed the G395M/F290LP setting, but we only use the significantly deeper GLIMPSE-D G395M observations here. Multiple images of RXCJ2248 were identified and observed in program #2478. Topping et al. (2024) utilized these data by coadding the spectra of the individual images. In contrast, only the brightest image (ID3) was observed in the GLIMPSE-D Survey. To ensure consistency, we therefore restricted our analysis to the G140M and G235M spectra of ID3 obtained in program #2478. As a result, our G140M and G235M measurements are not directly comparable to those presented by Topping et al. (2024).

The data were reduced using v0.9.8 of the msaexp pipeline (Brammer 2022), following the standard routines described in de Graaff et al. (2025); Heintz et al. (2025); Valentino et al. (2025). Briefly, level-2 calibrated products from MAST are subject to a series of custom corrections that account for e.g., $1/f$ noise, bar vignetting, and detector bias. We used the “local” nodded background subtraction. 2D spectra were drizzled onto a common wavelength grid and 1D spectra were optimally extracted using a profile model that accounts for e.g., the wavelength-dependent PSF and offsets from the nominal position expected from the catalog. Line centers were measured for the strongest emission lines in the G395M spectrum (i.e., H δ , H γ , [O III] $\lambda 4364$, H β , [O III] $\lambda\lambda 4960, 5008$, He I $\lambda 5877$, H α , He I $\lambda 7067$) and used to determine a redshift of $z = 6.1025 \pm 0.0013$. Note that the bluest portion of the G395M tends to favor a slightly lower redshift (i.e., $z \sim 6.1000$), while the reddest portion favors a slightly higher redshift (i.e., $z \sim 6.1034$). The three individual 1D extracted spectra were then normalized to the common continuum flux scale of the first spectrum at rest-

Table 1. Properties of RXCJ2248-ID3

JWST/NIRSpec Observations		
Grating/Filter	t_{exp} (s)	PI/PID
G140M/F100LP	6215	Stark/2478
G235M/F170LP	1576	Stark/2478
G395M/F290LP	107228	Fujimoto & Naidu/9223
Measured Properties		
Property	Value	Reference
R.A.	+22:48:45.81	This work
Decl.	−44:32:14.95	This work
z	6.1025 ± 0.0013	This work
μ	6.8877	Furtak et al. (2025)
R_{eff} (pc)	$19.5^{+13.99}_{-4.72}$	Claeyssens (2025)
M_* ($M_{\odot}$)	$4.6^{+21.1}_{-2.3} \times 10^7$	Claeyssens (2025)
Σ_* ($M_{\odot} \text{ pc}^{-2}$)	$1.1^{+5.2}_{-0.3} \times 10^4$	Claeyssens (2025)
SFR ($M_{\odot} \text{ yr}^{-1}$)	154	This work, § 5.3
Σ_{SFR} ($M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$)	6.45×10^4	This work
t_{age} (Myr)	$1.6^{+11.9}_{-0.9}$	Claeyssens (2025)
$12+\log(\text{O}/\text{H})$	7.749 ± 0.023	This work, § 4.3.1
$\log(\text{N}/\text{O})$	-0.390 ± 0.035	This work, § 4.3.2

NOTE— *Top:* JWST/NIRSpec observations of RXCJ2248-ID3, including archival observations from PID 2478 (PI: Stark) and very deep GLIMPSE-D observations from PID 9223 (PI: Fujimoto & Naidu). Columns 1–3 list the grating/filter, exposure time, and principle investigator/PID. *Bottom:* Measured global properties of RXCJ2248-ID3. The R.A. and Decl. are the extraction coordinates for RXCJ2248-ID3. The redshift was determined from the GLIMPSE-D spectrum emission lines. GLIMPSE imaging was used to determine the lensing model magnification, μ . Effective radius of the RXCJ2248-ID3 clump, stellar mass, and current massive star population age are from the SED modeling of Claeyssens (2025), while the SFR was determined from the narrow-component, collisions-corrected $\text{H}\alpha$ flux (see § 5.3), all corrected for the lensing factor. The metallicity and relative N/O abundance were determined using the direct method.

wavelengths of $\sim 6000\text{--}62000 \text{ \AA}$ prior to co-adding. Spectral coaddition was performed as a weighted average using the inverse variance as the weight.

The resulting spectrum, shown in Figure 2, covers an observed wavelength range $\sim 2.8\text{--}5.5 \mu\text{m}$, which corresponds to a rest-optical range of $\sim 3900\text{--}7740 \text{ \AA}$. Note that the third pointing (dashed slits in Figure 1) has reduced wavelength coverage such that the blue end begins at ~ 4265 . The deep GLIMPSE-D spectra provide unparalleled S/N (> 5 at $5100 \text{ \AA}$ continuum) that enable rest-optical diagnostics typically reserved for nearby galaxies.

2.2. Emission Line Measurements

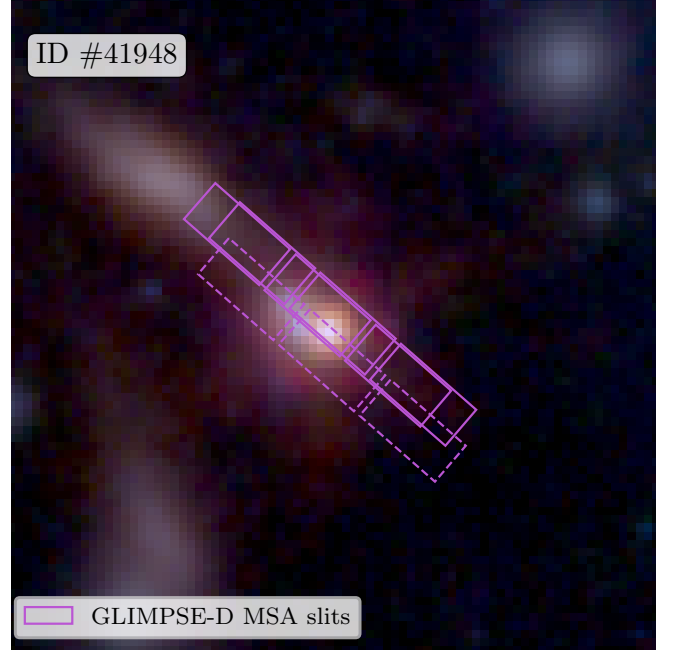


Figure 1. JWST/NIRSpec MSA slits targeting RXCJ2248-ID3 for each of the three exposures in the GLIMPSE-D program. The two pointings that are closely aligned (solid purple regions) have the same wavelength coverage, while the pointing offset to the lower left (dashed region) has somewhat reduced blue coverage. All three pointings were used in the spectrum coaddition.

In order to perform a consistent analysis of our data, we measure emission line fluxes for both the archival spectra and the new GLIMPSE-D spectra presented here. We fit neighboring emission lines simultaneously using Gaussian profiles with the `LMfit` package in `python`. Purely nebular lines (i.e., lines without possible stellar contributions or resonant effects) close in wavelengths were constrained to have the same full width at half maximum (FWHM) velocity widths. Additionally, the relative wavelength spacing between lines was constrained to laboratory values and doublets with constant flux ratios set by atomic physics were constrained to their theoretical values, with small uncertainty allowances. The uncertainties on the line fluxes were estimated as the standard error derived from the least-squares minimization in `LMfit`, which considers the uncertainty on the Gaussian profile and linear continuum.

Broad emission components are clearly visible at the base of some of the emission lines in the GLIMPSE-D spectrum of RXCJ2248-ID3. Such broad emission features can be produced by stellar winds, shocks, or turbulence. Since He II $\lambda 1640$ and $\lambda 4687$ emission lines can be affected by stellar winds, we fit these features with an unconstrained Gaussian width. Using the `jwst-msa` package (de Graaff et al. 2024), we deconvolved all measured FWHMs with the modeled wavelength-dependent line spread function (LSF). We

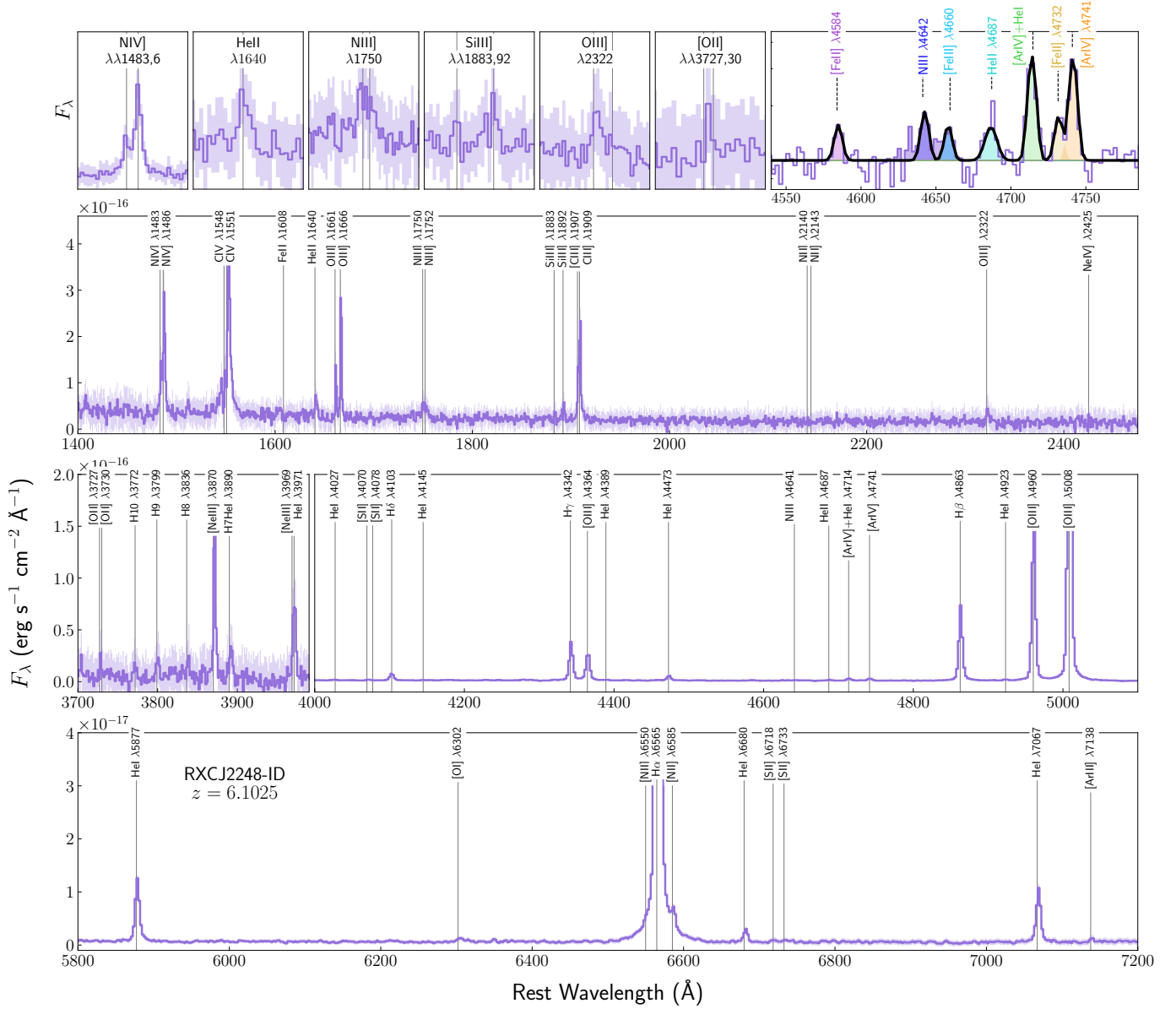


Figure 2. *JWST*/NIRSpec rest-frame UV and optical spectra of RXCJ2248-ID3 highlighting the first object known with simultaneously detected emission from N^+ , N^{+2} , and N^{+3} (see, also, [Topping et al. 2024](#)) and WR features. The 2nd row shows the main emission UV emission line detections from the archival G140M/F100LP spectrum, with significant detections of several high-ionization emission lines, including N IV] $\lambda\lambda 1483, 1486$, C IV $\lambda\lambda 1548, 1550$, He II $\lambda 1640$, O III] $\lambda\lambda 1661, 1666$, N III] $\lambda 1750$, and C III] $\lambda\lambda 1907, 1909$. The 3rd row shows the blue end of the optical spectrum, where the left hand panel shows the archival G235M/F170LP spectrum, which includes the low-ionization [O II] $\lambda\lambda 3727, 3729$ doublet. The right hand panel of the 3rd row and the 4th row shows the extremely high S/N GLIMPSE-D optical spectrum, enabling detections of several weak features. Some of the important features to this work are highlighted in the zoom in panels in the top row. In particular, the last panel reveals the most distant WR detection to date, with the $\lambda 4650$ WR bump showing emission from N III $\lambda 4642$, indicative of nitrogen enrichment from WN stars.

found the He II lines to be broadened compared to purely nebular lines. For the He II $\lambda 4687$ line, the velocity width is $528 \pm 100 \text{ km s}^{-1}$, which is more than two times broader than the narrow nebular H β component with $v_{\text{FWHM}} = 243 \pm 25 \text{ km s}^{-1}$.

The strongest rest-optical H and [O III] emission lines have complex profiles with both narrow and broad emission components. To fit these profiles, we tested three different multi-component profile combination fits for the H α + [N II] complex. For all three fits, the narrow H α and [N II] $\lambda\lambda 6550, 6585$ lines were fit by Gaussians with a single velocity width, but the broad component was fit with either: (1) a single Gaussian profile, (2) two Gaussian profiles, or (3) a single exponential profile. The single broad Gaussian profile fit had strong residuals near the center of the broad component, so did not provide a good fit to the observed emission profile. Both the double Gaussian profile and the exponential profile provided relatively good visual fits, but the double Gaussian fit had a lower reduced chi-squared ($\chi^2_{\text{2Gauss}} = 0.93$ vs $\chi^2_{\text{exp.}} = 1.52$) and Bayesian Inference Criteria ($\text{BIC}_{\text{2Gauss}} = 36$ vs $\text{BIC}_{\text{exp.}} = 87$), and so was adopted as the better statistical fit.

The right panel of Figure 3 shows the best multi-component fit to the H α + [N II] complex. Since all kinematically-similar lines in the Balmer emission series arise from the same gas, we expect the H β and H γ profiles to be well fit by scaling the H α best fit. Therefore, we constrained the velocity widths of the H β and H γ emission components to match the narrow + double broad Gaussian H α fit, accounting for the wavelength-dependent LSF. We found excellent fit results, with similarly small reduced- χ^2 and BIC values. This means that the H I lines are well fit by a profile with (1) a strong, narrow ($\sim 250 \text{ km s}^{-1}$) nebular component, (2) a moderate ($\sim 20\%$ of total flux), broad component ($\sim 670 \text{ km s}^{-1}$), and (3) a weak ($\sim 10\%$ of total flux), very broad ($\sim 2530 \text{ km s}^{-1}$) component.

The [O III] $\lambda\lambda 4960, 5008$ doublet lines are also well fit by a narrow Gaussian plus double Gaussian broad component profile, with the relative fluxes of each component constrained to the theoretical ratio. While the narrow component FWHM was set to the velocity width of the narrow Balmer lines, convolved with the LSF, we allowed the FWHM of the two broad [O III] components to vary freely and found widths of $\sim 890 \text{ km s}^{-1}$ and $\sim 2980 \text{ km s}^{-1}$, respectively. The similarity between the [O III] and H I velocity widths of the broad components argues against emission from an AGN directly (where high densities cause collisional de-excitation of [O III]) and is more consistent with stellar or AGN driven winds. Interestingly, the broad components of the H I lines compose a larger fraction of their total flux ($\sim 20\%$ and 10% , respectively) than [O III] ($\sim 10\%$ and 5% , respectively).

The resulting fit to the H β + [O III] $\lambda\lambda 4960, 5008$ complex is shown in the middle panel of Figure 3 to be an excellent fit,

with minimal residuals. The exquisite S/N of the GLIMPSE spectrum also reveals broad wings on the [O III] $\lambda 4364$ profile, as seen in the left panel of Figure 3. Therefore, we also applied the narrow Gaussian plus double Gaussian broad component profile to [O III] $\lambda 4364$, constraining the velocity widths to the values measured for [O III] $\lambda\lambda 4960, 5008$.

Double broad components with similar velocity widths (750 and 2500 km s^{-1} , respectively) are seen in the $z \sim 0$ extreme emission line galaxies, J1044+0353 and J1418+2102, reported in Berg et al. (2021). However, each broad component observed in these nearby analogs only accounts for 1% – 3% of the total H I flux. This sort of broad component emission from the Balmer H and [O III] lines with widths (1000 – 2000 km s^{-1}) and fractional fluxes of 1% – 2% is commonly found in spectra of blue compact dwarf galaxies (BCDs; e.g., Izotov et al. 2006; Izotov & Thuan 2007). This suggests that bulk motion of the gas is typical in these metal-poor, bursty environments, but for a larger mass of gas in RXCJ2248-ID3.

The sensitive accounting of broad component emission afforded by the deep GLIMPSE-D spectra is important, as even a small fraction of broad emission around H emission line can significantly affect the fit to weak lines such as [N II] $\lambda\lambda 6550, 6585$ (e.g., Berg et al. 2021). In RXCJ2248-ID, the broad components compose a significant fraction of the total H and [O III] fluxes, and so are critical to properly measure not only the [N II] $\lambda 6585$ emission, but also the [O III] $\lambda 4364$, H β , [O III] $\lambda\lambda 4960, 5008$, and H α narrow line fluxes. For this reason we adopt the narrow-line fluxes from our best multi-component fits for the remaining analysis; we reserve further investigation of the the broad emission for a forthcoming paper.

2.3. Reddening Correction

The observed Balmer decrement of the narrow H α /H β lines is $F_{\text{H}\alpha}/F_{\text{H}\beta} = 3.30$, implying a moderate amount of dust is present. This value disagrees with the results of Topping et al. (2024), who measured an observed decrement of 2.55 ± 0.05 that they found to be consistent with no dust attenuation. However, the higher S/N spectra presented here allow a more robust fitting of the broad components, including the H γ line. Thus, we also examined the H β /H γ ratio, finding a decrement of the narrow lines of $F_{\text{H}\beta}/F_{\text{H}\gamma} = 2.10$ that is consistent with very little dust.

The reddening due to dust, characterized by $E(B-V)$, was determined by comparing the observed Balmer decrements with the theoretical Balmer ratios assuming case B and the extinction law parameterized by Cardelli et al. (1989). The $E(B-V)$ value for a given Balmer ratio was determined iteratively until convergence, recomputing each iteration the H I theoretical ratio using the updated electron temperature from the reddening-corrected [O III] $\lambda 4364/\lambda 5008$ flux ratio and

density from the reddening-corrected N IV] $\lambda 1483/\lambda 1487$ flux ratio. In this way, the reddening, electron temperature, and electron density were solved for simultaneously and consistently. Note that the observed [O III] $\lambda 4364/\lambda 5008$ flux ratio leads to unphysical temperatures (i.e., above the limit set by H cooling of $\sim 2.5 \times 10^4$ K), and thus a physical and robust solution requires high densities to properly account for the $\lambda 5008$ flux that is missing due to collisionally de-excitation. Further, [Martinez et al. \(2025\)](#) recently showed that densities derived from both optical and UV diagnostics under the true volume-averaged density in multi-phase, high-density systems, with severe under-prediction from the optical diagnostics. Therefore, it is necessary to use UV density diagnostics in high-density environments, though the true density will still be underestimated in multi-phase gas (see, e.g., Figure 11 of [Martinez et al. 2025](#)).

A higher Balmer decrement from $F_{H\alpha}/F_{H\beta}$ than from $F_{H\gamma}/F_{H\beta}$ can arise under high-density conditions, where collisional excitation selectively enhances the $H\alpha$ flux relative to $H\beta$ and $H\gamma$. To assess whether such an enhancement is physically plausible, we examined the `CLOUDY` photoionization models ([Chatzikos et al. 2023](#); [Gunasekera et al. 2023](#)) presented in [Martinez et al. \(2025\)](#), which span a wide range of nebular densities (up to $n_e = 10^9 \text{ cm}^{-3}$). For the nebular conditions determined in this work (i.e., T_e , $\log U$, Z , N/O; see Section 4.3), densities of $n_e \sim 10^6 \text{ cm}^{-3}$ are needed to produce the observed $H\alpha$ enhancement while minimally affecting $H\beta$ and $H\gamma$. Although this density is roughly an order of magnitude higher than the values measured in [Topping et al. \(2024\)](#) and in this study (Section 4.1; Table 3), it could indicate that the ISM contains unresolved clumps of even higher density than the volume-weighted values probed by the density diagnostics used in this work. We, therefore, attribute the observed $H\alpha$ excess to collisional enhancement.

Accordingly, we adopted the reddening derived from $H\gamma/H\beta$, $E(B-V) = 0.053^{+0.114}_{-0.053}$ mag, and corrected all emission lines for the resulting (minimal) dust attenuation. We used the [Calzetti et al. \(2000\)](#) reddening law for the rest-UV emission lines ($\lambda < 3200 \text{ \AA}$) and the [Cardelli et al. \(1989\)](#) reddening law for the rest-optical emission lines ($\lambda > 3200 \text{ \AA}$). After applying the reddening correction, the $H\alpha/H\beta$ ratio still shows a collisional excess of 0.204 above the theoretical value; we correct for this excess and report a final $F_{H\alpha} = 1.011 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$. The adopted reddening and de-reddened line intensities are listed in Table 2. As the rest-UV and rest-optical spectra were obtained during different observing runs with distinct pointings and strategies, we report the UV lines relative to $F_{\text{C III]} \lambda \lambda 1907,1909} \times 100$ and the optical lines relative to $F_{H\beta} \times 100$, without applying any relative scalings between the two datasets.

Table 2. Rest UV+Optical Emission Line Fluxes

Ion+Wavelength ($\text{\AA}$)	$I(\lambda)/I(\text{C III])}$	EW ($\text{\AA}$)
N IV] $\lambda 1483.33$	42.78 ± 1.61	6.67
N IV] $\lambda 1486.50$	102.0 ± 0.82	15.9
He II $\lambda 1640.42$	22.46 ± 1.97	4.88
O III] $\lambda 1666.15$	85.84 ± 0.59	18.9
N III] $\lambda 1750^a$	38.59 ± 0.64	9.18
Si III] $\lambda 1883.00$	5.01 ± 3.25	1.32
Si III] $\lambda 1892.03$	8.25 ± 1.98	2.21
C III] $\lambda 1906.68$	35.11 ± 0.31	9.65
[C III] $\lambda 1908.73$	64.89 ± 0.25	17.9
Ion+Wavelength ($\text{\AA}$)	$I(\lambda)/I(H\beta)$	
[O II] $\lambda 3727^a$	4.09 ± 2.05	0.46
H γ $\lambda 4341.66^c$	47.41 ± 3.07	73.8
[O III] $\lambda 4364.44^c$	42.45 ± 1.92	66.5
He I $\lambda 4472.73$	8.90 ± 0.39	27.8
N III] $\lambda 4641.94$	1.40 ± 0.20	4.4
[Fe III] $\lambda 4659.80$	0.93 ± 0.19	2.9
He II $\lambda 4687.01$	1.33 ± 0.29	4.2
[Ar IV] $\lambda 4712.69^b$	2.30 ± 0.27	10.3
He I $\lambda 4714.46^b$	1.91 ± 0.19	3.0
[Fe III] $\lambda 4732.76$	1.22 ± 0.19	3.9
[Ar IV] $\lambda 4741.49$	4.10 ± 0.26	13.0
H β^c $\lambda 4862.71$	100.0 ± 4.4	356
[O III] $\lambda 4960.29^c$	230.5 ± 9.0	877
[O III] $\lambda 5008.24^c$	708.9 ± 27.5	2791
H α $\lambda 6564.60^{c,d}$	331.8 ± 14.4	1755
H α $\lambda 6564.60^{c,e}$	274.1 ± 11.9	1457
[N II] $\lambda 6585.27$	7.08 ± 0.91	12.8
[S II] $\lambda 6718.29$	0.68 ± 0.29	4.78
[S II] $\lambda 6732.67$	0.81 ± 0.30	4.74
$E(B-V)$	$0.053^{+0.114}_{-0.053}$	
$F_{\text{C III]}}$	8.48 ± 0.36	
$F_{H\beta}^c$	5.08 ± 0.11	

NOTE— Reddening-corrected emission-line intensities from the archival rest-UV and GLIMPSE rest-optical *JWST*/NIRSpec spectra for RXCJ2248-ID3. Note that no scaling was performed between the archival UV and GLIMPSE-D optical pointings (not needed for this work). Thus, UV fluxes are given relative to the $F_{\text{C III] } \lambda \lambda 1907,09} \times 100$ and optical fluxes are given relative to $F_{H\beta} \times 100$. The last three rows list the dust attenuation derived using the [Cardelli et al. \(1989\)](#) reddening law and the rest-frame C III] $\lambda \lambda 1907,09$ and H β flux in units of $10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$. Additionally, the fluxes reported here are for a single image of RXCJ2248 (ID3), whereas [Topping et al. \(2024\)](#) report fluxes for coadded spectra of multiple images.

^aNote that N III] $\lambda 1750$ and [O II] $\lambda 3727$ fluxes are the integrated values for the N III] $\lambda \lambda 1746, 1748, 1749, 1752, 1754$ quintuplet and [O II] $\lambda \lambda 3727, 3730$ doublet, respectively.

^b[Ar IV] $\lambda 4713$ +He I $\lambda 4714$ is a blended line profile at the observed resolution. Thus, the [Ar IV] $\lambda 4713$ is determined by subtracting the He I $\lambda 4714$ flux, which is predicted from the He I $\lambda 4473$ flux. ^cEmission line profile was best fit with a narrow Gaussian + two broad Gaussian components; only the corrected narrow line flux is listed here (see § 2.2 and Figure 3).

^dUncorrected for collisional-excitation.

^eCorrected for collisional-excitation.

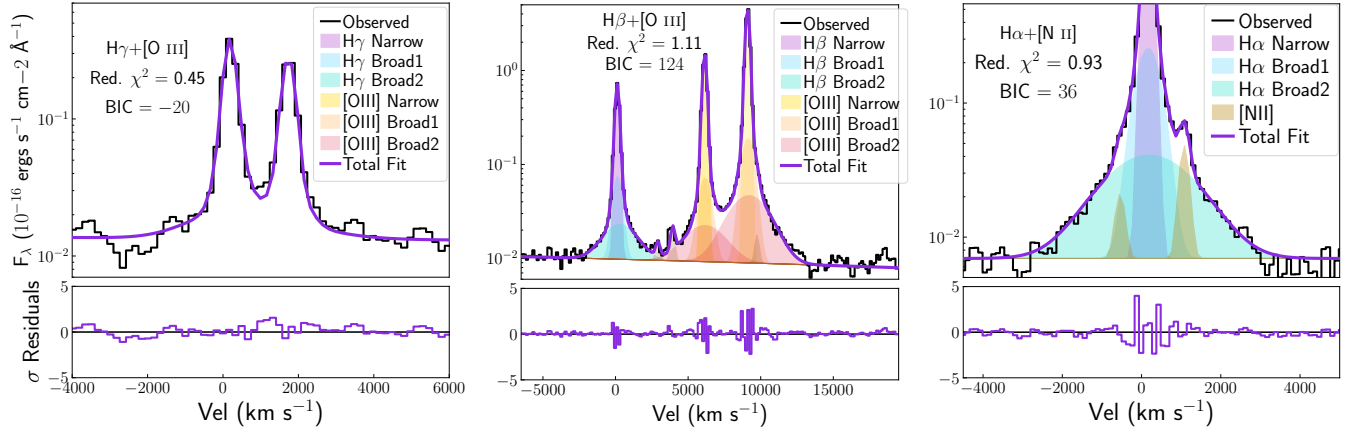


Figure 3. Multi-component emission line fits to the GLIMPSE spectrum of RXCJ2248-ID for $H\gamma$ $\lambda 4342$ + $[O\ III]$ $\lambda 4364$ (left panels), $H\beta$ $\lambda 4863$ + $[O\ III]$ $\lambda\lambda 4960,5008$ (middle panels), and $H\alpha$ $\lambda 6565$ + $[N\ II]$ $\lambda\lambda 6549,6585$ (right panels). When fit with single, narrow Gaussian components (e.g., purple and yellow filled Gaussians), all three line complexes show strong, broad component residual flux. The resulting best fit to each line is comprised of a single narrow Gaussian plus two broad Gaussians, where the relevant component velocity widths are tied together: The $H\alpha$ $\lambda 6565$ + $[N\ II]$ $\lambda\lambda 6549,6585$ complex fit provided the velocity width constraints for the H Balmer line narrow (purple Gaussians) and broad components (blue and green Gaussians) and, subsequently, the $H\beta$ $\lambda 4863$ + $[O\ III]$ $\lambda\lambda 4960,5008$ fit constrained the $[O\ III]$ narrow (yellow Gaussian) and broad (orange and red Gaussians) velocity widths that were then used in the $H\gamma$ $\lambda 4342$ + $[O\ III]$ $\lambda 4364$ fit. Note that faint lines (e.g., He I $\lambda 5017$) are not included in the fits shown here. Careful accounting for the residual broad flux has significant impact on the derived nebular reddening, temperature, metallicity, and N/O abundance.

3. WOLF RAYET STARS AT $Z = 6.1$

The WR stage of massive star evolution is an important, short-lived phase that can have significant effects on the chemical composition of the local ISM. We provide a brief overview here (see, e.g., [Crowther 2007](#), for a more thorough review). WR stars are massive stars that have entered the core He-burning phase and have lost their outer envelope either via strong stellar winds or due to binarity effects (i.e., stripping via Roche Lobe overflow or mergers). The first phase of WR stars occurs when the outer H layer has been ejected revealing the H core-burning products such that their spectra are characteristically He and N rich, but are H-poor. Such stars are known as nitrogen-type WR, or WN, stars, and are often identified by strong N III, N IV, and N V emission lines, especially the broad optical “blue bump” near $\lambda 4650$. The blue bump is a complex of features, including N III $\lambda\lambda 4634,4642$, C III $\lambda 4649,4667$, Fe III $\lambda 4660$, and He II $\lambda 4687$. Subsequently, stars that are massive enough for core He-burning and for their winds to remove their outer He envelope and expose the produced C, enter the WR-carbon, or WC, phase. WC stars also have strong, broad He II emission and strong C and O emission such that they are identified by the optical WR C IV $\lambda\lambda 5803,5814$ doublet. As a result, the typically very strong winds of the WR phase can produce significant N enrichment during the WN phase and drive strong C ejection during the WC phase.

The rest-frame UV and optical spectra of RXCJ2248-ID3 are shown in Figure 2, which can be used to characterize the WR nature of the stellar population in RXCJ2248-ID3. Both

the UV and optical He II emission features are kinematically broadened compared to the narrow nebular emission features in RXCJ2248-ID3, indicative of WR or very-massive star ($> 100 M_{\odot}$; VMS) winds. The upper right hand panel of Figure 2 highlights the blue bump spectral regime, showing weak, broad He II and N III $\lambda 4642$ in RXCJ2248-ID3, both of which are characteristic of metal-poor WN stars. Just redward of the N III $\lambda 4642$ line in the blue bump (but blueward of [Fe III]), a second less prominent emission feature is seen, but it is difficult to determine whether this is due to C III or O II emission, or both. Further, the red C IV bump isn’t detected, suggesting little to no contributions from WC stars in the spectrum. Thus, we only significantly detect the blue WR bump, suggesting that WN stars are likely present.

4. NEBULAR PROPERTIES

With the updated narrow component emission line fits presented in Section 2.2, we next determined the nebular properties of RXCJ2248-ID3. Following [Berg et al. \(2021\)](#), we adopt the expanded four-zone ionization model to account for the high ionization emission observed. In this model, the ionization potential energy ranges of N^+ , S^{+2} , O^{+2} , and He^{+2} define the low-, intermediate-, high-, and very high-ionization zones, respectively. For all calculations, we use the PyNeb package in python with the atomic data adopted in [Berg et al. \(2019\)](#), which includes a six-level atom model for oxygen in order to utilize the UV O III $\lambda 1666$ line. Note that $T_e[O\ III]$ and $n_e[N\ IV]$ were co-determined during the iterative reddening calculation (see § 2.3).

4.1. Temperature and Density

One of the unique characteristics of RXCJ2248-ID3 is its large number of density-sensitive emission line ratios. [Topping et al. \(2024\)](#) previously reported densities from the three UV line ratios of Si III] $\lambda 1883/\lambda 1892$, characterizing the intermediate-ionization zone, C III] $\lambda 1907/\lambda 1909$, characterizing the intermediate- to high-ionization zone, and N IV] $\lambda 1483/\lambda 1486$, characterizing the high- to very high-ionization zone. The new high-S/N optical spectra enables us to measure, for the first time, densities from the low-ionization [S II] $\lambda 6717/6731$ ratio and the high- to very high-ionization [Ar IV] $\lambda 4713/\lambda 4741$ ratio.

We use our narrow component de-reddened flux measurements to compute densities for all five line ratios and the high-ionization zone temperature from the [O III] $\lambda 4364/\lambda 5008$ ratio. We first simultaneously determined the [O III] temperature and N IV] density in the high-ionization zone to account for sensitivities of both diagnostics. We find a $T_e(\text{O}^{+2}) = 1.97 \pm 0.03 \times 10^4$ K and $n_e(\text{N}^{+3}) = 2.65_{-0.38}^{+0.45} \times 10^5 \text{ cm}^{-3}$, which is consistent with the density of $n_e(\text{N}^{+3}) = 3.1_{-0.4}^{+0.5} \times 10^5 \text{ cm}^{-3}$ reported by [Topping et al. \(2024\)](#), but lower than their temperature of $2.46 \pm 0.26 \times 10^4$ K due to our broad component fits of both [O III] $\lambda 4364$ and $\lambda 5008$. We then applied the $T_e - T_e$ relations of [Garnett \(1992\)](#) to estimate the intermediate- and low-ionization temperatures from $T_e(\text{O}^{+2})$.

The determined temperatures were used for the subsequent density calculations in their respective ionization zones. Note, however, that the [Ar IV] $\lambda 4713$ and He I $\lambda 4714$ lines are blended in the G395M grating. Therefore, we corrected the [Ar IV] $\lambda 4713$ flux for the He I $\lambda 4714$ contribution, predicting the He I $\lambda 4714$ flux from the measured He I $\lambda 4473$ flux and the theoretical He I $\lambda 4714/\lambda 4473$ ratio (~ 0.21 for the conditions in RXCJ2248-ID). The resulting densities, all of which fall within their respective diagnostic ranges, and temperatures are reported in Table 2.

Remarkably, RXCJ2248-ID3 is one of few galaxies, and the only galaxy yet at high-redshifts, to have significant ($> 3\sigma$) electron density measurements from five different ions that span a large ionization range ($\sim 10 - 77$ eV). Further, the densities in RXCJ2248-ID3 appear to be organized into an interesting nebular stratification. The UV emission lines trace the densest gas, with $n_e(\text{N}^{+3}) = 2.65 \times 10^5 \text{ cm}^{-3}$ in the highest ionization gas, followed by $n_e(\text{C}^{+2}) = 7.94 \times 10^4 \text{ cm}^{-3}$, and $n_e(\text{Si}^{+2}) = 4.77 \times 10^4 \text{ cm}^{-3}$. In contrast, the optical high ionization lines are emitted from regions of lower densities: the optical [Ar IV] diagnostic has an overlapping ionization energy range as the UV N IV] diagnostic, but a density that is an order of magnitude lower.

There are two possible interpretations of the measured array of densities. First, since the UV lines also have higher excitation energies, they could originate preferentially from

hotter, denser clumps. This would imply a strongly inhomogeneous ISM, in which compact, high-pressure structures dominate the UV line emission while somewhat more diffuse gas produces much of the optical emission. Alternatively, the multi-phase ISM may span a smaller dynamic range of densities than we measure due to the suppression of the optical diagnostics. [Martinez et al. \(2025\)](#) showed that for an ISM with a mix of low- (e.g., 10^3 cm^{-3}) and high-density gas (e.g., 10^5 cm^{-3}) such that the true volumetric mix is somewhere in between, the low-ionization optical diagnostics will always be significantly biased low, close to the low-density gas value until the fraction of high-density gas is very high (e.g., $> 95\%$). This effect is due to the low-critical densities of the [S II] lines ($n_{e,\text{crit}} \approx 2 \times 10^3 - 5 \times 10^3 \text{ cm}^{-3}$) such that emission from the high-density gas is collisionally-suppressed beyond detection. The magnitude of this effect decreases with increasing critical density such that [Ar IV] is moderately affected ($n_{e,\text{crit}} \approx 2 \times 10^4 - 2 \times 10^5 \text{ cm}^{-3}$) and the UV Si III], C III], and N IV] ($n_{e,\text{crit}} \approx 5 \times 10^4 - 5 \times 10^{10} \text{ cm}^{-3}$) are minimally affected, but still biased low. In this scenario, there would still be density stratification, but with smaller differences.

All together, the nebular diagnostics in RXCJ2248-ID3 support a picture of a multiphase nebula with density and temperature stratification, likely reflecting a clumpy ISM shaped by the feedback and local radiation field variations of bursty star formation (see, also, [Harikane et al. 2025b](#); [Usui et al. 2025](#); [Choustikov et al. 2025](#)). This picture is also consistent with the density stratification that has been reported for dwarf galaxies both near and far (e.g., [James et al. 2016](#); [Berg et al. 2021](#); [Mingozzi et al. 2022](#); [Ji et al. 2024](#); [Topping et al. 2024](#)), but with typical densities increasing with redshift (e.g., [Isobe et al. 2023](#); [Abdurro'uf et al. 2024](#); [Topping et al. 2025a](#); [Martinez et al. 2025](#)).

4.2. Ionization Parameter

The ionization parameter of RXCJ2248-ID3, $\log U$, determined using the typical $\text{O}_{32} = I_{\lambda 5008}/I_{\lambda 3727}$ diagnostic is reported in [Topping et al. \(2024\)](#) to be in the high range of $\log U = -0.5$ to -1 . We recompute the ionization parameter for RXCJ2248-ID3 using new O_{32} and $\text{N}_{43} = I_{\lambda 1483,1486}/I_{\lambda 1750}$ diagnostics from [Martinez et al. \(2025\)](#) that are calibrated for densities in the $10^2 \leq n_e (\text{cm}^{-3}) \leq 10^6$ range. We estimate a $\log U_{\text{int}} = -1.25 \pm 0.23$ using O_{32} , which is consistent with the value reported by [Topping et al. \(2024\)](#), and $\log U_{\text{high}} = -0.69 \pm 0.23$ using N_{43} , which is slightly high but both are very high ionization. Note, however, that the O_{32} diagnostic is very sensitive to the assumed density ([Martinez et al. 2025](#)), making this value highly uncertain in dense gas. In particular, we estimate $\log U_{\text{int}} = -0.57$ to -2.04 for densities of $n_e = 10^3$ to 10^5 cm^{-3} , respectively.

4.3. Abundances

Here we present direct-method abundances for RXCJ2248-ID3 using the measured temperatures and densities presented in § refsec:temden. To calculate the total or relative abundance of an element, we determine and sum the individual observed ions and then apply an ionization correction factor to account for unseen prominent ionization states. The abundance of an individual ionic species, X^i , relative to hydrogen is determined as:

$$\frac{N(X^i)}{N(H^+)} = \frac{I_{\lambda(i)} j_{H\beta}}{I_{H\beta} j_{\lambda(i)}}, \quad (1)$$

where $j_{\lambda(i)}$ is the emissivity determined for the appropriate ionization zone temperature and density. Given the tendency of the optical density diagnostics to severely under-estimate the density in high-density environments, we instead adopt the UV-derived densities. Note that abundances presented below have not been corrected for the fraction of atoms embedded in dust. However, the level of depletion onto dust grains is expected to be small for the low metallicity of RXCJ2248-ID3 (e.g., Rémy-Ruyer et al. 2014; Galliano et al. 2018; Roman-Duval et al. 2022). Details of elemental abundance determinations are given below.

4.3.1. Oxygen Abundance

We determine the total O/H abundance as the sum of the O^+/H^+ and O^{+2}/H^+ ionic abundances, determined from the [O II] $\lambda 3727$ and [O III] $\lambda \lambda 4960, 5008$ optical emission lines. We observe no strong contributions from O^0 or O^{+3} , indicating contributions from other ions are negligible. The resulting ionic and total oxygen abundances are presented in Table 2. Similar to Hayes et al. (2025) and Martinez et al. (2025), we find that one of the most significant effects of accounting for high densities is the resulting decrease in electron temperature and subsequent increase in oxygen abundance. In our work, this results both from accounting for the missing [O III] $\lambda 5008$ flux due to collisional de-excitation and from correcting the narrow emission for broad emission components at their base. Topping et al. (2024) also incorporated the high densities seen in RXCJ2248-ID3, but did not have the S/N to fit the broad emission components in both [O III] $\lambda 5008$ and $\lambda 4364$. As a result, we measure an oxygen abundance of $12 + \log(O/H) = 7.749 \pm 0.023$.

4.3.2. Relative N/O Abundance

The extraordinary simultaneous detections of [N II] $\lambda 6585$, [N III] $\lambda 1750$, and [N IV] $\lambda \lambda 1483, 1487$ enable multiple determinations of the N/O abundance. Therefore, we calculate

N/O abundances using four different ionic methods:

$$1. \frac{N}{O} = \frac{N^+}{O^+} \times \text{ICF} = \frac{N^+}{O^+} \times \left[\frac{X(N^+)}{X(O^+)} \right]^{-1} \quad (2)$$

$$2. \frac{N}{O} = \frac{N^{+2}}{O^{+2}} \times \text{ICF} = \frac{N^{+2}}{O^{+2}} \left[\frac{X(N^{+2})}{X(O^{+2})} \right]^{-1} \quad (3)$$

$$3. \frac{N}{O} = \frac{N^{+3}}{O^{+2}} \times \text{ICF} = \frac{N^{+3}}{O^{+2}} \left[\frac{X(N^{+3})}{X(O^{+2})} \right]^{-1} \quad (4)$$

$$4. \frac{N}{O} = \frac{N^+ + N^{+2} + N^{+3}}{O^+ + O^{+2}}, \quad (5)$$

where [O II] $\lambda 3727$ is used for the N^+/O^+ determination, [O III] $\lambda 1666$ is used for the N^{+2}/O^{+2} and N^{+3}/O^{+2} calculations, and $X(N^i)$ and $X(O^i)$ are the N and O ionization fractions, respectively. We use the density-dependent ICFs from Martinez et al. (2025), who provide prescriptions for densities of $n_e = 10^2, 10^3, 10^4, 10^5$, and 10^6 cm^{-3} . We, therefore, round our density measurements to the nearest order of magnitude, and use the intermediate-ionization $\log U$ for the N^+/O^+ ICF and the high-ionization $\log U$ for the N^{+2}/O^{+2} and N^{+3}/O^{+2} ICFs. The resulting N ICFs and N/O abundances are reported in Table 2.

The four N/O determinations of RXCJ2248-ID3 are in close agreement, far above the expected value for its metallicity. Visually, this is shown in the upper left-hand panel of Figure 5, which plots the relative N/O versus O/H abundance with RXCJ2248-ID3 marked by purple diamonds. The traditional N/O–O/H trend has been established by many $z \sim 0$ studies of H II regions and galaxies (gray points: Esteban et al. 2002; Pilyugin & Thuan 2005; van Zee & Haynes 2006; García-Rojas & Esteban 2007; López-Sánchez et al. 2007; Esteban et al. 2009; Berg et al. 2012; Esteban et al. 2014; Berg et al. 2016, 2019, 2020). The empirical trend is a bimodal relationship, with a flat trend due to primary (or metallicity-independent) N production at low-metallicities ($12 + \log(O/H) \lesssim 8.0$) and an increasing N/O trend with O/H as secondary (or metallicity-dependent) N production becomes increasingly important at higher metallicities ($12 + \log(O/H) \gtrsim 8.0$). As a visual guide, the primary N/O plateau from Berg et al. (2019) is shown as a dashed purple line and the empirical stellar curve from Nicholls et al. (2017, solid green line) is shown as an example of the full primary+secondary curve.

For comparison, we plot the high-quality high- z N/O measurements that were calculated in a consistent manner as the present work (with direct-method T_e and n_e determinations and n_e -dependent ICFs) by Martinez et al. (2025). N/O abundances determined using N^{+2}/O^{+2} are plotted as blue + symbols, while N^+/O^+ determinations are plotted as blue pentagons. Of these galaxies, the closest comparison to RXCJ2248-ID3 is CEERS-1019 (see, also, Marques-Chaves et al. 2024), while only GDS 3073 and GN-z11 have higher

relative N/O abundances and only GDS 3073 is more enhanced in N/O for its O/H abundance.

We find that all four ionic methods produce consistently high N/O values within their uncertainties, with a weighted mean of $\log(\text{N/O}) = -0.390 \pm 0.035$. This is an important result, as RXCJ2248-ID3 is the first galaxy to have consistently enhanced N/O abundances measured from both the rest-frame UV high-ionization and the optical low-ionization emission lines. Further, measuring consistent N/O values from three different ionic methods strengthens our confidence in the robustness of the N/O measurement. Uniform N/O across the ionization structure of the nebula is also a bit surprising: while there is strong evidence for a stratified, or perhaps very clumpy, density structure in RXCJ2248-ID, the N/O abundance appears to be well mixed.

4.3.3. Relative C/O Abundance

Measuring the carbon-to-oxygen (C/O) abundance provides a crucial comparative baseline for interpreting the origin of elevated N/O in RXCJ2248-ID3. Similar to N, C has a pseudo-secondary¹ production pathway, but the dominant nucleosynthetic sources and timescales differ for C and N. Briefly, both C and O are primarily produced in massive stars ($> 8 M_{\odot}$) on relatively short timescales such that the C/O ratio is a relatively stable tracer of massive star yields. In contrast, N can be produced by both massive stars (e.g., through rotational mixing and WR winds) and intermediate-mass AGB stars ($3 - 8 M_{\odot}$), which release N on longer timescales. Therefore, N/O and C/O together serves as diagnostics of the recent star formation history, constraining the recent enrichment mechanisms of galaxies (e.g., Garnett 1990; Henry et al. 2000; Chiappini et al. 2003; Pérez-Montero & Contini 2009; Berg et al. 2019; Pérez-Montero et al. 2021).

Relative C/O abundances are typically determined using the C III] $\lambda\lambda 1907, 1909/\text{O III] } \lambda 1666$ ratio to calculate $\text{C}^{+2}/\text{O}^{+2}$ and assuming that $\text{C/O} \approx \text{C}^{+2}/\text{O}^{+2}$. This method is sometimes used alone owing to the fact that C^{+2} and O^{+2} have somewhat similar ionization potentials (24.38 and 35.12 eV, respectively), $\lambda 1666$ and $\lambda\lambda 1907, 1909$ have similar excitation potentials (~ 6.5 and ~ 7.5 eV, respectively), and the integrated fluxes of $\lambda 1666$ and $\lambda\lambda 1907, 1909$ are not sensitive to collisional de-excitation for the densities measured here. However, for the high-ionization nebulae in RXCJ2248-ID3, it is important to account for contributions from the C^{+3} species and any unseen species. We note that the C IV $\lambda\lambda 1548, 1550$ doublet is clearly observed in the rest-

UV spectrum of RXCJ2248-ID3, but these lines are resonant and can be affected by the C IV stellar wind feature and ISM absorption, and so, determining the intrinsic flux and subsequent C^{+3} abundance is challenging. Instead, we use an ICF determined from the photoionization models presented in Martínez et al. (2025) such that

$$\frac{\text{C}}{\text{O}} = \frac{\text{C}^{+2}}{\text{O}^{+2}} \times \text{ICF} = \frac{\text{C}^{+2}}{\text{O}^{+2}} \times \left[\frac{X(\text{C}^{+2})}{X(\text{O}^{+2})} \right]^{-1}. \quad (6)$$

We used the $\log U_{\text{int}}$ and a density of $n_e(\text{C}^{+2}) \sim 10^5 \text{ cm}^{-3}$ to determine the C ICF. The resulting C ICF and C/O abundance are reported in Table 2.

The C/O and C/N abundances for RXCJ2248-ID3 are plotted in the upper middle and right-hand panels of Figure 5. Empirical trends of C/N at $z \sim 0$ are found to be flat, albeit with significant scatter (see shading in Figure 5, suggesting that the dominant nucleosynthetic mechanisms of carbon are similar to those of nitrogen (e.g., Garnett et al. 1999; Esteban et al. 2014; Berg et al. 2016, 2019). However, while the production of both C and N appear to be metallicity-dependent, the scatter in their trend is consistent with differing production timescales due to stars of different masses. Thus, the variations observed in CNO abundance patterns of high- z galaxies may be the result of taking a snapshot of many galaxies at different times since their most recent onset of star formation.

RXCJ2248-ID3 appears to have a similar CNO abundance pattern to other high- z N-emitters, characterized by enhanced N/O, but deficient C/N for its O/H abundance. In this scenario, RXCJ2248-ID3 is also relatively C/O-deficient. This suggests that these high- z galaxies are enhanced in N relative to both O and C. If massive stars in the WN phase are present, they will have recently produced ^{14}N at the expense of ^{12}C through the CNO cycle, meaning C used as a catalyst in the cycle initiation will have been *consumed* as N is removed during the bottleneck step via dredged up, preventing C return at cycle completion. Thus, C/N-deficiency is consistent with a recent, intense episode of N-enrichment and C-consumption from WR feedback. Conversely, if both N/O and C/O were elevated in tandem, it could point to broader enrichment by massive stars, such as enrichment from both WN and WC stars, whose contributions increase at higher metallicities.

5. A SHORT WINDOW OF INTENSE WR NITROGEN ENRICHMENT

We have presented evidence for WN stars in RXCJ2248-ID3 in two forms: first, the rest-frame optical WR blue bump discussed in Section 3 and shown in Figure 2; second, a qualitative comparison of the CNO abundances to patterns expected for WR stars in § 4.3 and Figure 5. Below, we ex-

¹ There are no known secondary nucleosynthetic production methods for C; only the primary triple- α process is known to produce C. However, other processes, such as metal-dependent line-drive stellar winds, may be responsible for the empirical increasing trend in C/O–OH, hence the term *pseudo-secondary*.

Table 3. Nebular Conditions and Abundances for RXCJ2248-ID3

Property	Ion. E (eV)	Used	Value
Temperatures:			
$T_{e,\text{high}}$ meas. (K)	35.11 – 54.93	$n_e(\text{N}^{+3})$	$1.97 \pm 0.03 \times 10^4$
$T_{e,\text{int.}}$ used (K)	23.33 – 34.83	$n_e(\text{C}^{+2})$	$1.51 \pm 0.02 \times 10^4$
$T_{e,\text{low}}$ used (K)	13.62 – 35.11	$n_e(\text{Si}^{+2})$	$1.68 \pm 0.02 \times 10^4$
Densities:			
$n_e(\text{N}^{+3})$ (cm^{-3})	47.45 – 77.47	$T_{e,\text{high}}$	$2.65^{+0.45}_{-0.38} \times 10^5$
$n_e(\text{Ar}^{+3})$ (cm^{-3})	40.74 – 59.81	$T_{e,\text{high}}$	$1.75^{+0.26}_{-0.22} \times 10^4$
$n_e(\text{C}^{+2})$ (cm^{-3})	24.38 – 47.89	$T_{e,\text{int.}}$	$7.94^{+0.69}_{-0.65} \times 10^4$
$n_e(\text{Si}^{+2})$ (cm^{-3})	16.35 – 33.49	$T_{e,\text{int.}}$	$4.77^{+5.68}_{-2.33} \times 10^4$
$n_e(\text{S}^{+})$ (cm^{-3})	10.36 – 23.33	$T_{e,\text{low}}$	$1.22^{+4.71}_{-0.45} \times 10^4$
O Abundances:			
$\text{O}^+/\text{H}^+ (\times 10^{-5})$	13.62 – 35.11	$T_{e,\text{int.}}; n_e(\text{Si}^{+2})$	0.153 ± 0.086
$\text{O}^{+2}/\text{H}^+ (\times 10^{-5})$	35.11 – 54.93	$T_{e,\text{high}}; n_e(\text{Ar}^{+2})$	5.459 ± 0.211
$12 + \log(\text{O}/\text{H})$			7.749 ± 0.023
Ionization Parameters:			
$\log U_{\text{int.}}(\text{O}_{32})$	13.62 – 54.93	$n_e = 10^4 \text{ cm}^{-3}$	-1.25 ± 0.23
$\log U_{\text{high}}(\text{N}_{43})$	29.60 – 77.47	$n_e = 10^5 \text{ cm}^{-3}$	-0.69 ± 0.10
N Abundances:			
$\text{N}^{+3}/\text{O}^{+2}$	47.45 – 77.47	$T_{e,\text{high}}; n_e(\text{N}^{+3})$	0.278 ± 0.043
$\text{N}^{+2}/\text{O}^{+2}$	29.60 – 47.45	$T_{e,\text{high}}; n_e(\text{C}^{+2})$	0.145 ± 0.070
N^+/O^+	14.53 – 29.60	$T_{e,\text{low}}; n_e(\text{Si}^{+2})$	0.387 ± 0.259
$\text{ICF}(\text{N}^{+3}/\text{O}^{+2})$	47.45 – 77.47	$T_{e,\text{high}}; n_e(\text{N}^{+3})$	1.542
$\text{ICF}(\text{N}^{+2}/\text{O}^{+2})$	29.60 – 47.45	$T_{e,\text{high}}; n_e(\text{C}^{+2})$	2.545
$\text{ICF}(\text{N}^+/\text{O}^+)$	14.53 – 29.60	$T_{e,\text{low}}; n_e(\text{Si}^{+2})$	0.814
$\log(\text{N}/\text{O})_{\text{N}^{+3}}$			-0.368 ± 0.052
$\log(\text{N}/\text{O})_{\text{N}^{+2}}$			-0.434 ± 0.070
$\log(\text{N}/\text{O})_{\text{N}^+}$			-0.502 ± 0.259
$\log(\text{N}/\text{O})_{\text{all}}$			-0.375 ± 0.055
$\langle \log(\text{N}/\text{O}) \rangle$			-0.390 ± 0.035
C Abundances:			
$\text{C}^{+2}/\text{O}^{+2}$	24.38 – 47.89	$T_{e,\text{high}}; n_e(\text{C}^{+2})$	0.107 ± 0.014
$\text{ICF}(\text{C}^{+2}/\text{O}^{+2})$	24.38 – 47.89	$T_{e,\text{high}}; n_e(\text{C}^{+2})$	1.497
$\log(\text{C}/\text{O})$			-0.796 ± 0.052

NOTE—Ionic and total abundances for RXCJ2248-ID3. Column 1 lists the property, while Column 2 lists the associated ionization potential energy range (eV), Column 3 lists the temperature and/or density used in the calculation, and Column 4 provides the final values. Note that all calculations reported here only used the narrow components when multi-component fits were performed. Two ionization parameters are reported for the O_{32} and N_{43} indicators from [Martinez et al. \(2025\)](#). The oxygen abundance was determined using the archival $[\text{O II}] \lambda 3727$ detection and the new $[\text{O III}] \lambda 5008$ fit. N/O was determined using four different ion+ICF (from [Martinez et al. 2025](#)) combinations: (1) optical N^+/O^+ ; (2) UV $\text{N}^{+2}/\text{O}^{+2}$; (3) UV $\text{N}^{+3}/\text{O}^{+2}$; and (4) combination $(\text{N}^+ + \text{N}^{+2} + \text{N}^{+3})/(\text{O}^+ + \text{O}^{+2})$. C/O was determined from the archival UV emission lines only.

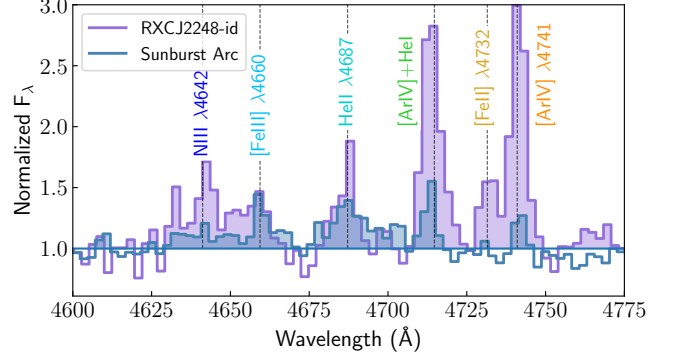


Figure 4. The blue WR region of the optical spectrum of RXCJ2248-ID3 (purple) is shown in comparison to the $z \sim 3$ Sunburst Arc spectrum from [Rivera-Thorsen et al. \(2024\)](#), which has been convolved to $R \sim 1000$ to match RXCJ2248-ID3. Both galaxies show characteristic signs of hosting WN stars, but RXCJ2248-ID3 shows striking N III $\lambda 4642$ emission that is much stronger than the Sunburst Arc. On the other hand, the Sunburst Arc shows broader He II emission, which is expected for a more metal-rich galaxy as stellar winds scale with metallicity.

amine the plausibility and impact of these WN stars. First, in § 5.1, we compare RXCJ2248-ID3 to expected trends for WR stars with decreasing metallicity. Second, in § 5.2, we use chemical evolution models and stellar yields to test whether WN stars can reproduce the observed CNO abundance pattern. Third, in § 5.3, we assess whether the mass of ionized N inferred for RXCJ2248-ID3 could plausibly be produced by its current stellar population. Together, these lines of investigation suggest that the enhanced N/O and suppressed C/O in RXCJ2248-ID3 represent a short-lived enrichment phase, unique to metal-poor, highly star-forming galaxies in the early universe (§ 5.4).

5.1. WN Stars: The Dominant WR Phase at Low-Metallicity

To date, no individual WR stars have been directly observed at metallicities as low as RXCJ2248-ID3 ($Z \sim 0.1 Z_{\odot}$). The scarcity of WR stars in such metal-poor environments is expected, as mass loss through stellar winds scales with metallicity. We show the trend of the number of WC/WN star as a function of metallicity in Figure 6. The observed number of WC/WN stars in M31 ($\sim 175\% Z_{\odot}$), the Milky Way (MW; $Z_{\odot}$), M33 ($\sim 40\% - 110\% Z_{\odot}$), the Large Magellanic Cloud (LMC; $\sim 40\% Z_{\odot}$), and the Small Magellanic Cloud (SMC; $\sim 20\% Z_{\odot}$) suggest that the number of WN/WC number ratio increases with decreasing metallicity (e.g., [Meynet & Maeder 2005](#); [Crowther 2007](#); [Massey et al. 2015](#); [Neugent & Massey 2019](#)). This is because weaker metal line-driven winds, rotation, or binary effects in metal-poor stars may be able to expose their nitrogen-rich layers and initiate the WN phase, but be insufficient to strip the stellar He atmosphere and reveal the carbon-rich core to initiate the WC phase.

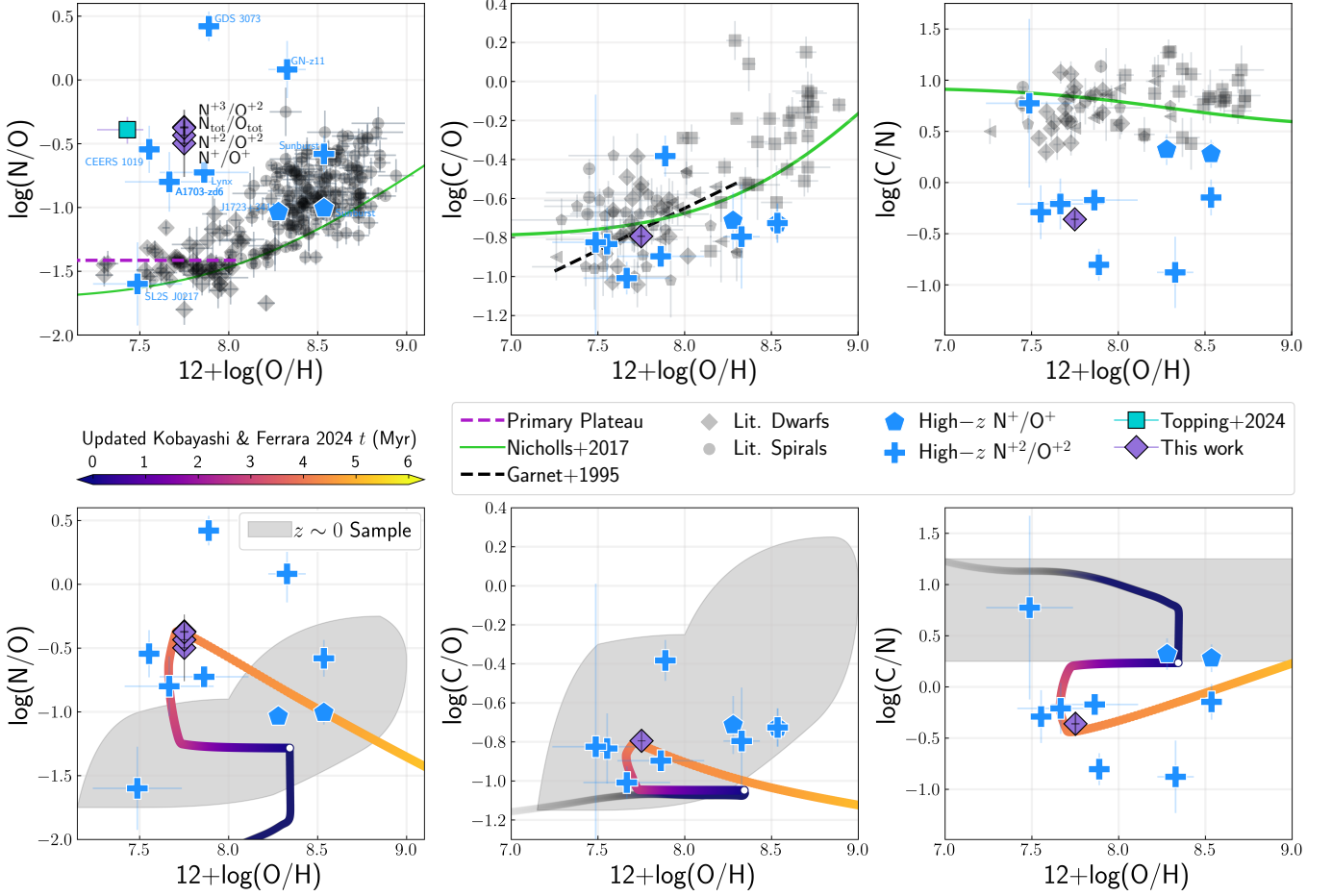


Figure 5. Relative C and N abundance trends versus metallicity. Nitrogen to oxygen ratio versus oxygen abundance for star-forming galaxies is plotted in the left panels, while carbon to oxygen ratio versus oxygen abundance is plotted in the middle panels, and carbon to nitrogen abundance versus oxygen abundance is plotted in the right panels. *Top row:* RXCJ2248-ID3 is shown relative to the observed $z \sim 0$ trend and other high- z galaxies. The abundances for RXCJ2248-ID3 are shown as purple diamonds, where multiple N/O points show the measurements for each ionic N/O calculation method. The typical bi-modal N/O trend is characterized by local dwarf (gray diamonds; van Zee & Haynes 2006; Berg et al. 2012; Berg et al. 2016, 2019) and spiral galaxy (gray circles; Esteban et al. 2002; Esteban et al. 2009; Esteban et al. 2014; Pilyugin & Thuan 2005; García-Rojas & Esteban 2007; López-Sánchez et al. 2007; Berg et al. 2020) H II region measurements. The primary N/O plateau from Berg et al. (2019) is shown as a dashed purple line, while the solid green line is an empirical stellar curve from Nicholls et al. (2017). Additional C/O literature measurements for dwarf galaxies are from Peña-Guerrero et al. (2017) and Senchyna et al. (2017). High-redshift ($z > 2$) abundances from Martinez et al. (2025) are plotted as blue plus signs for galaxies with UV N^+/O^{+2} derived abundances and pentagons for optical N^+/O^{+2} derived abundances. *Bottom row:* The same observed samples are shown as the top row, but with the $z \sim 0$ sample represented by the shaded gray regions. The observed abundances of RXCJ2248-ID3 are compared to updated dual-burst chemical evolution models of Kobayashi & Ferrara (2024, string of circles), color-coded by age since onset of the second burst. The models have been modified to reproduce both the enhanced N/O and relatively deficient C/O observed for RXCJ2248-ID3, which requires enrichment from WN but very little WC enrichment, as expected at low-metallicities.

Thus, if WR stars form at $Z \sim 10\% Z_{\odot}$, they are expected to be overwhelmingly WN-type.

The spectral features of RXCJ2248-ID3 support the picture of WN star feedback at low metallicity. As shown in Figure 2, the He II emission is moderately broadened, the N III $\lambda 4642$ line in the blue bump is prominent, and there is no evidence for the red bump C IV feature, all consistent with the presence of WN stars at low metallicity. The weakness of

the He II emission in terms of both flux and velocity width is expected for the low-metallicity environment of RXCJ2248-ID3 ($\sim 10\% Z_{\odot}$) due to reduced wind velocities and mass-loss rates (Sander et al. 2020). Similarly weak WN features have also been reported in the nearby metal-poor galaxy SBS 0335-052 (Izotov et al. 2006) and the $z \sim 2.3$ lensed galaxy the Sunburst Arc (Rivera-Thorsen et al. 2024).

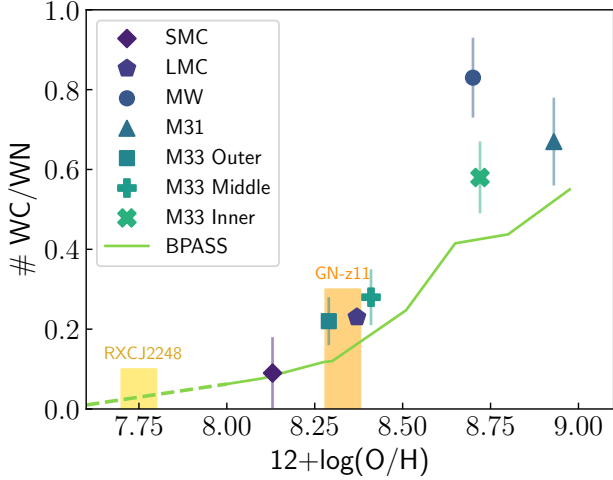


Figure 6. Observed and theoretical ratios of WC/WN star numbers as a function of metallicity. Observed values for the SMC, LMC, Milky Way, and M31 were compiled by Neugent & Massey (2019), while newer values for M33 come from Neugent & Massey (2023). For comparison, we also plot the trend presented in Massey et al. (2017) for BPASSv2.0 binary stellar population synthesis burst models for $12+\log(\text{O}/\text{H}) > 8$ (solid line green line), which we extrapolate to lower metallicities (dashed line). We note the metallicity for GN-z11 determined by Martinez et al. (2025), which is consistent with a WC/WN ratio of $\sim 0.1-0.2$, and the metallicity for RXCJ2248-ID3 from the current work, which predicts a much lower WC/WN ratio of $\sim 0.03-0.10$. Therefore, very little carbon enrichment from WC stars is expected for RXCJ2248-ID3.

We plot the WR blue bump profile of RXCJ2248-ID3 relative to the Sunburst Arc in Figure 4. For ease of comparison, we convolve the Sunburst Arc $R \sim 2700$ JWST/NIRSpec spectrum to the $R \sim 1000$ resolution of the RXCJ2248-ID3 spectrum. These spectra immediately reveal similar profiles, but with three distinct differences: (1) RXCJ2248-ID3 exhibits higher ionization, as evidenced by the strong [Ar IV] $\lambda\lambda 4713, 4741$ emission; (2) the He II stellar wind feature is significantly broader in the Sunburst Arc ($\text{FWHM} = 1370 \text{ km s}^{-1}$) than RXCJ2248-ID3 ($\text{FWHM} = 530 \text{ km s}^{-1}$), consistent with stronger stellar winds at the higher metallicity (Sunburst Arc: $12+\log(\text{O}/\text{H}) \sim 8.5$ or $Z \sim 0.7 Z_{\odot}$; Martinez et al. 2025); and (3) the WR N III $\lambda 4642$ line is much stronger in RXCJ2248-ID3, which lack WR C IV $\lambda\lambda 5803, 5814$ emission, while the Sunburst Arc exhibits both. These differences support a scenario in which the Sunburst Arc hosts both WC and WN stars, but the more metal-poor RXCJ2248-ID3 hosts a young population of WN stars with no or very little WC contribution.

5.2. Relative Chemical Enrichment from WN Stars

With first discovery of WN stars in a high-redshift galaxy, we now explore their chemical yields as a source of the abundance pattern in RXCJ2248-ID3. Charbonnel et al. (2023)

performed a comparable analysis for the extreme N/O ratio observed in GN-z11 and found that such rapid nitrogen enrichment could arise from normal massive stars with $M_{*} \sim 20-120 M_{\odot}$ or from supermassive stars ($M_{*} \gtrsim 1000 M_{\odot}$) in proto-globular cluster environments. Their results and those of Marques-Chaves et al. (2024) further demonstrated that the short-lived WN-like phase can produce large N/O ratios within a few Myr of the burst, consistent with the timescales inferred here, but that the observed C/O ratios are only compatible over a very short time interval.

Building on this theoretical groundwork, Kobayashi & Ferrara (2024) developed a dual-burst chemical evolution model to match GN-z11’s enrichment pattern in which a second, brief episode of star formation triggers a narrow ($\lesssim 1$ Myr) WR-dominated enrichment phase. Finally, Marques-Chaves et al. (2024) modeled the CNO abundance pattern of CEERS-1019 using nitrogen yields from rotating massive stars and tested whether a young, WR-dominated stellar population could reproduce the observed enrichment. These models provide a valuable physical framework for linking stellar yields to galaxy-scale abundance evolution at early times. We extend the methodologies outlined by these works to RXCJ2248-ID3, applying an updated version of the Kobayashi & Ferrara (2024) dual-burst chemical evolution model and performing a similar order-of-magnitude check on the total nitrogen mass budget as Marques-Chaves et al. (2024).

We begin by examining the dual-burst chemical evolution model of Kobayashi & Ferrara (2024), which was fine-tuned to reproduce the enhanced N/O in GN-z11 (reported by Maiolino et al. 2023). This model invokes two bursts of star formation, where the second triggers a narrow ($\lesssim 1$ Myr) phase of WR-dominated enrichment. While the model can easily reach the N/O enrichment level of RXCJ2248-ID3, it was also designed to yield the higher O/H and C/O abundances observed in GN-z11 than RXCJ2248-ID3, which was achieved, in part, by enrichment from WC stars. The updated O/H abundance for GN-z11 determined by Martinez et al. (2025) makes it consistent with some carbon enrichment from WC stars, as shown in Figure 6. However, with a metallicity of only $Z \sim 0.10 Z_{\odot}$, the WR population in RXCJ2248-ID3 is expected to consist of few WC stars, and so an updated chemical evolution model is needed to match its unique CNO abundance pattern.

We modify the Kobayashi & Ferrara (2024) dual burst model to be more appropriate for the metal-poor conditions in RXCJ2248-ID3. In particular, the galactic chemical evolution (GCE) model uses the same star formation history and the standard IMF (for $0.01-120 M_{\odot}$) as in the fiducial model in Kobayashi & Ferrara (2024) but reduces the contribution from WC stars. C/O ratios of the nucleosynthesis yields vary depending on the uncertain nuclear reaction rates (e.g.,

$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$) and the treatment of convection and mass-loss (Kobayashi et al. 2006). In the updated model, ^{12}C and ^{16}O yields are taken from Kobayashi et al. (2020) for all mass ranges of stars but the contributions from the WC wind phase is scaled to $\sim 15\%$ in order to match empirical and theoretical expectations that most massive stars will have insufficient winds to remove their He envelopes at such low metallicities.

We plot the updated metal-poor dual burst model in the bottom row of Figure 5 as a time-series of points that are color-coded by the age since the second burst. In this model, the observed N/O, O/H, and C/O abundances of RXCJ2248-ID3 are reached simultaneously ~ 4.2 Myr after the onset of the second burst. This young age is consistent with enrichment from WN stars and with the derived clump age of $1.6_{-0.9}^{+11.9}$ Myr (Claeyssens 2025). Thus, the N/O-enhanced and relatively C/O-deficient conditions in RXCJ2248-ID3 are produced by a short-lived evolutionary phase following intense, bursty star formation.

We note that the duration and impact of the WN phase may be significantly extended if the stars evolve in binary systems. In the Limongi & Chieffi (2018) single-star models, the WN phase typically lasts $\sim 0.03 - 0.3$ Myr and, due to the metallicity-dependent winds, require high initial masses ($\sim 40 M_{\odot}$) to expose the He- and N-rich layers. However, in close binaries, envelope stripping via mass transfer or common-envelope evolution can induce WR phases in lower-mass stars ($20 - 30 M_{\odot}$), largely independent of the stellar metallicity. This channel can significantly prolong the WN lifetime (up to ~ 1 Myr) depending on the binary mass ratio and separation (e.g., Eldridge et al. 2017; Götzberg et al. 2019; Aguilera-Dena et al. 2022). As a result, binary evolution may enhance both the frequency and duration of the chemically-selective N/O enrichment phase like that observed in RXCJ2248-ID. Future work incorporating binary WR pathways into chemical evolution models may, therefore, be essential for capturing the full range of nitrogen feedback in low-metallicity starbursts at high-redshift. Taken together, the massive star enrichment scenario presented here, and explored in Charbonnel et al. (2023), Marques-Chaves et al. (2024), and Kobayashi & Ferrara (2024), demonstrate that selective enrichment of nitrogen by WN-dominated feedback can naturally reproduce the observed CNO abundance pattern in compact, low-metallicity starbursts like RXCJ2248-ID3.

We can now paint a full picture of the ISM of RXCJ2248-ID. The consistency of N/O across ions spanning a wide range of ionization potentials further suggests that the WN-enriched material has been efficiently mixed throughout the ionized gas. This apparent chemical homogeneity does not contradict the strong density and temperature stratification inferred from our diagnostics: a clumpy or multiphase

ISM can remain compositionally uniform if the enriched ejecta are well dispersed. Given the extreme compactness of RXCJ2248-ID3 ($R_e \approx 20$ pc), the characteristic dynamical and sound-crossing times are only a few $\times 10^5$ yr, comparable to or shorter than the duration of the WN phase itself. Under such conditions, turbulent and radiative mixing can rapidly homogenize the heavy-element yields, producing a chemically uniform yet physically structured nebula.

5.3. The N Mass Budget

A crucial point of validation is whether an intense burst of star formation so early in the universe could have produced the amount of N present in RXCJ2248-ID3. Similar to the analysis in Marques-Chaves et al. (2024), we test this by first estimating the ionized nitrogen mass using:

$$M_{\text{N}_{\text{ion}}} = M_{\text{H}_{\text{ion}}} \left(\frac{\text{N}}{\text{H}} \right)_{\text{ion}} \left(\frac{m_{\text{N}}}{m_{\text{H}}} \right), \quad (7)$$

where the atomic mass ratio is $m_{\text{N}}/m_{\text{H}} = 14$ and N/H is the nitrogen abundance of the ionized gas. The hydrogen gas mass M_{H} is derived from the H α luminosity:

$$M_{\text{H}} = \frac{m_{\text{H}} L_{\text{H}\alpha}}{h \nu_{\text{H}\alpha} \alpha_{\text{H}\alpha}^{\text{eff}} n_e} \sqrt{\epsilon}, \quad (8)$$

where $m_{\text{H}} = 1.67 \times 10^{-27}$ kg, $h = 6.626 \times 10^{-27}$ erg·s, $\nu_{\text{H}\alpha}$ is the frequency of the H α emission line, and $\alpha_{\text{H}\alpha}^{\text{eff}} = 6.078 \times 10^{-14}$ cm³ s⁻¹ is the Case B effective recombination coefficient for H α assuming a $T_e = 1.97 \times 10^4$ K. We estimate the H α luminosity using a luminosity distance of $d_L(z = 6.1025) = 1.817 \times 10^{29}$ cm, the collision-corrected narrow component flux, and a magnification of $\mu = 6.8877$ (Furtak et al. 2025). We use the H α luminosity of 6.09×10^{43} erg s⁻¹, with the EW(H α)=1458 Å, to derive the star formation rate (SFR) using simulation-based SFR(H α) calibration from Kramarenko et al. (2025). This method was developed to be more appropriate for the bursty conditions at high-redshift than traditional calibrations and gives a SFR= $154 M_{\odot} \text{ yr}^{-1}$, which is roughly two times higher than the SED-derived SFR for a constant SFH from Topping et al. (2024). Adopting a filling factor of $\epsilon = 0.01$, assuming a compact starburst (e.g., Kennicutt 1984; Stasińska & Schaerer 1997), and the measured N/H value, we calculate the ionized nitrogen mass to be $M_{\text{N}_{\text{ion}}} \approx 920 M_{\odot}$ for a density of 10^4 cm^{-3} .

We then compute the total nitrogen mass that can be produced by the $4.6 \times 10^7 M_{\odot}$ of stars in the RXCJ2248-ID clump Claeyssens (2025). We compute the integrated nitrogen yield produced by the modified Kobayashi & Ferrara (2024) model over the duration of the second burst (~ 4.2 Myr). This results in a total N mass of $1.25 \times 10^3 M_{\odot}$, implying that $\sim 74\%$ of the gas is ionized when matched to the expected ionized N mass ($\sim 920 M_{\odot}$) from the crudely calculated observed value. Thus, WN stars formed in a recent

burst within a compact, high-density, and very clumpy / inhomogeneous (low-filling-factor) environment can plausibly explain the N mass in RXCJ2248-ID3, even at low metallicity ($\sim 10\% Z_{\odot}$), and without invoking a top-heavy IMF or exotic enrichment channels.

5.4. The Ephemeral Imprint of WN Star on High- z Galaxies

The prominence of N/O enhancement at high-redshift but relative rarity in local star-forming galaxies likely reflects a combination of environmental conditions and evolutionary factors that are unique to the early universe. To examine the likely environments, we plot the SFR surface density versus EW of $H\beta$ in Figure 7 for both high- z N emitters and local star-forming galaxies with enhanced SFRs from the COS Legacy Archive Spectroscopic Survey (CLASSY; Berg et al. 2022; James et al. 2021). The $z \gtrsim 6$ galaxies, such as RXCJ2248-ID3, exhibit compact morphologies ($R_e \lesssim 10^2$ pc) that lead to much higher SFR surface densities than seen at $z \sim 0$, as well as bursty star formation histories that favor the rapid buildup of massive stars capable of entering the short-lived WN phases ($M_{\star} > 20 M_{\odot}$). The high- z N emitters also have high $H\beta$ EWs ($> 200 \text{ \AA}$) that are indicative of young current bursts of star formation (< 5 Myr). This suggests that compactness alone is not enough to observe enhanced N/O; we must also observe these galaxies at the fleeting moments of very young bursts when WR stars are most active.

Figure 7 suggests a scenario of elevated N/O at low metallicity being preferentially seen in galaxies with high SFR surface densities and young stellar ages (e.g., Topping et al. 2024; Schaerer et al. 2024; Martinez et al. 2025). Marques-Chaves et al. (2024) also suggest that the elevated N/O and high-ionization spectrum of CEERS-1019 trace a short evolutionary window of a $\lesssim 5$ Myr burst dominated by WN-like feedback. Further, the theoretical models of Charbonnel et al. (2023) predict that such phases are characteristic of young, dense stellar systems, potentially analogous to protoglobular clusters, reinforcing that our observed WN-driven enrichment is a natural outcome of clustered, bursty star formation at early times. These results are all consistent with the WN scenario in RXCJ2248-ID3 presented here.

At low metallicity, weaker stellar winds require higher initial masses for stars to reach the WR phase, so a larger total stellar mass must form in a burst to produce a detectable population of WN stars. In compact high- z galaxies, this condition is naturally met in systems with high star formation rate surface densities, which statistically sample the upper IMF more fully and produce a detectable population of WN stars (e.g., Brinchmann et al. 2008; Shirazi & Brinchmann 2012). Furthermore, the WR enrichment signature is short-lived: it must be captured during the brief WN-dominated phase ($t_{\text{burst}} \lesssim 5$ Myr and $\Delta t_{\text{WN}} \lesssim 0.3$ Myr), before dilution

from WC stars, core-collapse supernovae, or delayed AGB enrichment. These timing constraints imply that only a small fraction of the star-forming galaxies will be caught in this phase. The detection of WR-driven N/O enhancement at high-redshift thus reflects a brief evolutionary stage where intense, rapid feedback from WN stars briefly imprints non-uniform elemental enrichment patterns (i.e., elevated N/O), that are expected to be quickly washed away. As soon as the system evolves beyond the WN phase, subsequent WC or CCSN yields will rapidly dilute the N excess and alter the overall abundance pattern (e.g., increasing C/O, lowering N/C). This special timing requirement was also suggested by Marques-Chaves et al. (2024) for other N-emitters.

Recently, Topping et al. (2025b) showed that galaxies with significant N IV] emission (which corresponds to extreme N/O enhancement), are found exclusively amongst galaxies with extreme [O III]+ $H\beta$ equivalent widths (EW) of 2600–4200 $\text{\AA}$. Galaxies with such high [O III]+ $H\beta$ EWs are in the upper 2% tail of the EW distribution at $z \gtrsim 4$. This strongly suggests that N/O outliers are confined to the youngest stellar populations undergoing their most intense bursts of star formation (e.g., Endsley et al. 2023; Matthee et al. 2023; Endsley et al. 2025; Topping et al. 2025b).

In this context, Topping et al. (2025b) found that 30% of galaxies with $\text{EW}_{[\text{O III}]+\text{H}\beta} > 2000 \text{ \AA}$ show strong nitrogen emission, corresponding to $\sim 0.6\%$ of their UV-selected parent population. If this 0.6% population corresponds to enhanced N/O during the $\Delta t_{\text{WN}} \sim 0.3$ Myr WN phase, it would imply a characteristic burst timescale of ~ 50 Myr. A practical consequence is that young bursts substantially increase the light-to-mass ratios and, thus, the likelihood of detection in flux-limited samples (e.g., Sun et al. 2023; Mason et al. 2023; Muñoz et al. 2023). Therefore, the observed frequency of strong nitrogen emitters at fixed M_{UV} is likely biased high relative to their intrinsic abundance (e.g., at fixed stellar mass). Given the detectability bias toward burst phases, this t_{burst} may represent a lower limit, with the true interval plausibly longer. This timescale is supported by recent analyses of the scatter in the star-forming main sequence and time-resolved SFR indicators at $z \sim 3-9$ that suggest burst cycles of tens-of-Myr timescales (albeit with broad distributions, e.g., Simmonds et al. 2025). Thus, the combination of extreme-EW selection and N IV] frequency provides a novel timing argument that WN-driven enrichment is tightly coupled to very young, transient starburst phases at high redshift.

Taken together, the arguments presented in this work suggest that nitrogen outliers are not exotic exceptions, but rather a brief, WN-enriched phase that any high-redshift galaxy with sufficiently high star formation rate surface density can pass through. In contrast, numerous low-redshift WR galaxies exhibit young populations that include WN and WC stars but show little or no N/O enhancement (e.g., Izotov et al.

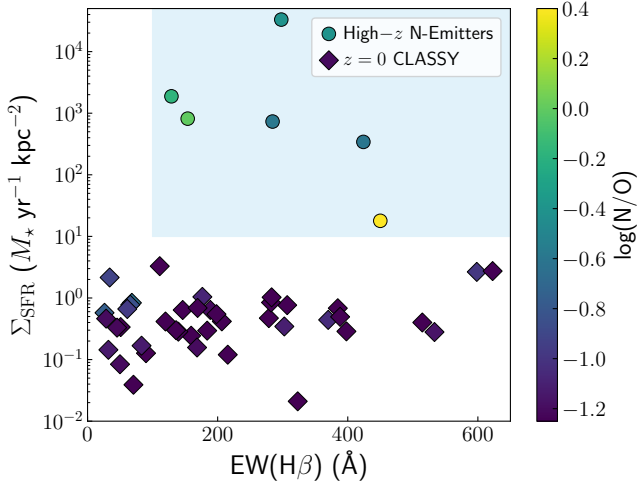


Figure 7. Star formation rate surface density versus $H\beta$ equivalent width for high-redshift N-emitters versus $z \sim 0$ galaxies from the CLASSY survey, which have enhanced SFRs similar to $z \sim 2-3$ galaxies. high-redshift N-emitters are only observed at young ages ($\lesssim 5$ Myr), as indicated by the high $H\beta$ equivalent widths ($EW > 200$ Å), and in compact, dense environments ($\Sigma_{\text{SFR}} > 10 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$). Note that RXCJ2248-ID3 is plotted here using the properties derived from Topping et al. (2024) for continuous star formation to be consistent with the other N-emitter measurements.

2006). This difference underscores that similar stellar populations do not guarantee the same chemical signatures; instead, the extreme densities, compactness, and rapid mixing timescales of high-redshift starbursts likely make WN-driven enrichment both more pronounced and more transient. In this view, high-redshift N/O outliers are not anomalies, but rather are the chemical fingerprints of galaxies caught mid-burst, showing fleeting yet inevitable markers of early galactic evolution.

6. CONCLUSIONS

We have presented the first discovery of extreme nitrogen enrichment from Wolf Rayet nitrogen stars (WN) in the metal-poor ($\sim 10\% Z_{\odot}$), high surface-density ($1.1 \times 10^4 M_{\odot} \text{ pc}^{-2}$), high-redshift ($z = 6.1025$), lensed galaxy RXCJ2248-ID3. These measurements were made possible by exceptionally deep JWST/NIRSpec medium-resolution spectroscopy of RXCJ2248-ID3, obtained as part of the GLIMPSE-D survey. The unprecedented depth and S/N of the GLIMPSE-D spectrum allow spectral measurements typically limited to the nearby universe, including consistent broad components in the Balmer series and [O III] $\lambda 4364$ and $\lambda 4960, 5008$ lines, faint [Ar IV] $\lambda 4713, 4741$ emission, and signatures of WR stars. Specifically, we detected emission characteristic of WN-type stars, including strong N III] $\lambda 4642$ and broadened He II $\lambda 1640$ and $\lambda 4687$ emission, marking RXCJ2248-

ID3 as the most distant galaxy with direct WR features to date.

We performed a detailed nebular analysis, self-consistently measuring the reddening, narrow-component [O III] temperature, and densities from five different diagnostics across a wide ionization range. The ISM of RXCJ2248-ID3 is high density, with measured densities in the range of $1.22 \times 10^4 \text{ cm}^{-3} \leq n_e \leq 2.65 \times 10^5 \text{ cm}^{-3}$. We measure a low reddening value of $E(B-V) = 0.053^{+0.114}_{-0.053}$ from the $H\gamma/H\beta$ ratio, but find an excess in the $H\alpha/H\beta$ ratio of 0.204 due to collisional excitation of $H\alpha$.

RXCJ2248-ID3 also shows strong evidence for nebular density stratification, with systematically higher densities in the highest-ionization gas and UV emission tracing gas at higher densities than those traced by optical diagnostics. This structure implies a highly clumpy, multi-phase ISM. We note that such high-density, multi-phase gas leads to densities from optical diagnostics that are biased to the low end of the density range due to their low critical densities. Therefore, we recommend using UV density diagnostics as they are more robust in high-density environments: $n_e(\text{Si}^{+2})$, $n_e(\text{C}^{+2})$, and $n_e(\text{N}^{+3})$ trace the densities in the low-, intermediate-, and high-ionization gas, respectively. As a result, we measure a direct-method metallicity of $12 + \log(\text{O}/\text{H}) = 7.749 \pm 0.023$.

Using the full rest-UV+optical spectra, we present the first robust, consistent measurements of N/O abundance in any galaxy using all three ionization stages of nitrogen (N^+/O^+ , $\text{N}^{+2}/\text{O}^{+2}$, $\text{N}^{+3}/\text{O}^{+2}$). The uniformity of our N/O measurements suggests that the N/O enrichment is spatially extended and well-mixed throughout the ionized ISM. Empirical trends suggest C/O should follow a similar trend as N/O and, thus, also be enhanced. In contrast, we find C/O to be significantly depleted relative to N/O, suggesting non-uniform elemental enrichment likely driven by WN stars with little to no contribution from WC stars.

The CNO abundance pattern is best reproduced by a modified version of the dual-burst chemical evolution model from Kobayashi & Ferrara (2024) that reduces the contribution from WC stars relative to WN stars, as expected in metal-poor environments. The resulting short-lived WN phase and ejects N-rich, C-poor material. Further, we use this chemical evolution model to assess whether the observed N mass can plausibly arise from the recent star formation in RXCJ2248-ID3 and estimate an ionized N mass of $1250 M_{\odot}$. This value is consistent with the N mass estimated from the observed emission lines of $\sim 920 M_{\odot}$ if $\sim 74\%$ of the N gas is ionized.

These results demonstrate that standard stellar evolution models can reproduce both the CNO pattern and the total nitrogen mass observed without invoking an exotic IMF or enrichment channel. The uniform N/O ratios across multiple ionization zones further suggest that the WN yields were

rapidly mixed into a relatively pristine ambient ISM, preserving the global enhancement observed in RXCJ2248-ID3. Although RXCJ2248-ID3 exhibits strong density and temperature stratification, this structural complexity does not necessarily imply chemical inhomogeneity. The consistent N/O ratios across ions tracing vastly different physical conditions indicate that the enriched material was efficiently dispersed throughout the multiphase ISM. In such a compact ($R_e \approx 20$ pc), high-pressure environment, turbulent and radiative mixing can homogenize the chemical composition on timescales comparable to, or shorter than, the brief WN phase itself, yielding a chemically uniform yet physically clumpy nebula.

Importantly, the abundance pattern and physical conditions observed in RXCJ2248-ID3 can only be explained if the galaxy is caught during a narrow evolutionary window within a few Myr of a massive, compact starburst when WN stars dominate chemical feedback. At low metallicity, stars require higher initial masses to reach the WR phase, making such enrichment episodes rare and dependent on sufficiently high SFRs to fully populate the upper IMF. Further, the WN phase itself is extremely short-lived ($\sim 0.03 - 0.3$ Myr), and easily masked by subsequent WC winds, CCSNe, or AGB stars contributions. These timing and SFR constraints make WR-driven N/O enhancement a rare phenomenon associated with extreme starburst conditions occurring at high-redshift, but which are scarce in the local universe.

Our results suggest that the WN-driven N/O enrichment we observe is not a peculiar property of a single system, but rather a brief phase that essentially all high-redshift galaxies with sufficiently high SFR surface densities to produce significant numbers of WN stars likely undergo. In particular, the work of Topping et al. (2025b) can be used to link N/O outliers to the most extreme [O III]+H β equivalent widths. The observed frequency of such equivalent widths combined with the short lifetime of the WN phase implies a burst cycle of order ~ 50 Myr, consistent with galaxies repeatedly cycling through short, bursty episodes of enrichment. Thus, the GLIMPSE-D spectrum of RXCJ2248-ID3 provides not only the first direct evidence of WN stars shaping the chemical evolution of $z > 6$ galaxies, but also a timing argument that situates N/O outliers as a natural, fleeting, phase of high-redshift star formation.

Taken together, our findings are a glimpse into a short-lived phase of chemically-selective enrichment from WN stars at cosmic dawn, providing a physically self-consistent solution to the extreme N/O enhancement and relative C/O depletion observed in RXCJ2248-ID3 and other high-redshift galaxies. Thus, this galaxy serves as a benchmark case for interpreting chemically enriched, stratified, multiphase starbursts in the early universe.

Facilities: JWST (NIRSpec)

Software: `astropy` (Astropy Collaboration et al. 2013, 2018, 2022), `calwebb`, `jupyter` (Kluyver et al. 2016), `numpy` version 1.26 (Harris et al. 2020), `PyNeb` version 1.1.14 (Luridiana et al. 2015), `python`, `lmfit` (Newville et al. 2015), `mpfit` (Markwardt 2009), `scipy.optimize.curve_fit`, `BAGPIPES` (Carnall et al. 2018), `BPASS` version 2.14 (Eldridge et al. 2017), `cloudy` version 23.01 (Chatzikos et al. 2023; Gunasekera et al. 2023), `msaexp` pipeline version 0.9.8 (Brammer 2022)

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REFERENCES

- Abdurro'uf, Larson, R. L., Coe, D., & others. 2024, *ApJ*, 973, 47, doi: [10.3847/1538-4357/ad6001](https://doi.org/10.3847/1538-4357/ad6001)
- Aguilera-Dena, D. R., Langer, N., Antoniadis, J., et al. 2022, *A&A*, 661, A60, doi: [10.1051/0004-6361/202142895](https://doi.org/10.1051/0004-6361/202142895)
- Asplund, M., Amarsi, A. M., & Grevesse, N. 2021, *A&A*, 653, A141, doi: [10.1051/0004-6361/202140445](https://doi.org/10.1051/0004-6361/202140445)
- Astropy Collaboration, Price-Whelan, A. M., Lim, P. L., et al. 2022, *ApJ*, 935, 167, doi: [10.3847/1538-4357/ac7c74](https://doi.org/10.3847/1538-4357/ac7c74)
- Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., et al. 2018, *AJ*, 156, 123, doi: [10.3847/1538-3881/aabc4f](https://doi.org/10.3847/1538-3881/aabc4f)
- Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, *A&A*, 558, A33, doi: [10.1051/0004-6361/201322068](https://doi.org/10.1051/0004-6361/201322068)
- Atek, H., et al. 2025, *apj*
- Balestra, I., Vanzella, E., Rosati, P., & others. 2013, *A&A*, 559, L9, doi: [10.1051/0004-6361/201322620](https://doi.org/10.1051/0004-6361/201322620)
- Berg, D. A., Chisholm, J., Erb, D. K., et al. 2021, *ApJ*, 922, 170, doi: [10.3847/1538-4357/ac141b](https://doi.org/10.3847/1538-4357/ac141b)
- Berg, D. A., Erb, D. K., Auger, M. W., Pettini, M., & Brammer, G. B. 2018, *ApJ*, 859, 164
- Berg, D. A., Erb, D. K., Henry, R. B. C., Skillman, E. D., & McQuinn, K. B. W. 2019, *ApJ*, 874, 93, doi: [10.3847/1538-4357/ab020a](https://doi.org/10.3847/1538-4357/ab020a)
- Berg, D. A., James, B. L., King, T., et al. 2022, *ApJS*, 261, 31, doi: [10.3847/1538-4365/ac6c03](https://doi.org/10.3847/1538-4365/ac6c03)
- Berg, D. A., Pogge, R. W., Skillman, E. D., et al. 2020, *ApJ*, 893, 96, doi: [10.3847/1538-4357/ab7eab](https://doi.org/10.3847/1538-4357/ab7eab)
- Berg, D. A., Skillman, E. D., Henry, R. B. C., Erb, D. K., & Carigi, L. 2016, *ApJ*, 827, 126
- Berg, D. A., Skillman, E. D., Marble, A., et al. 2012, *ApJ*, 754, 98
- Boone, F., Clément, B., Richard, J., et al. 2013, *A&A*, 559, L1, doi: [10.1051/0004-6361/201322552](https://doi.org/10.1051/0004-6361/201322552)
- Brammer, G. 2022, *msaexp: NIRSpc analysis tools*, 0.3, doi: [10.5281/zenodo.7299500](https://doi.org/10.5281/zenodo.7299500)
- Brinchmann, J., Kunth, D., & Durret, F. 2008, *A&A*, 485, 657, <https://arxiv.org/abs/0805.1073>
- Bunker, A. J., Saxena, A., Cameron, A. J., et al. 2023, *A&A*, 677, A88, doi: [10.1051/0004-6361/202346159](https://doi.org/10.1051/0004-6361/202346159)
- Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, *ApJ*, 533, 682
- Cameron, A. J., Katz, H., Rey, M. P., & Saxena, A. 2023, *MNRAS*, 523, 3516, doi: [10.1093/mnras/stad1579](https://doi.org/10.1093/mnras/stad1579)
- Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, *ApJ*, 345, 245
- Carnall, A. C., McLure, R. J., Dunlop, J. S., & Davé, R. 2018, *MNRAS*, 480, 4379, doi: [10.1093/mnras/sty2169](https://doi.org/10.1093/mnras/sty2169)
- Castellano, M., Napolitano, L., Fontana, A., et al. 2024, *ApJ*, 972, 143, doi: [10.3847/1538-4357/ad5f88](https://doi.org/10.3847/1538-4357/ad5f88)
- Charbonnel, C., Schaerer, D., Prantzos, N., et al. 2023, *A&A*, 673, L7, doi: [10.1051/0004-6361/202346410](https://doi.org/10.1051/0004-6361/202346410)
- Chatzikos, M., Bianchi, S., Camilloni, F., et al. 2023, *RMxAA*, 59, 327, doi: [10.22201/ia.01851101p.2023.59.02.12](https://doi.org/10.22201/ia.01851101p.2023.59.02.12)
- Chiappini, C., Romano, D., & Matteucci, F. 2003, *MNRAS*, 339, 63
- Choustikov, N., Katz, H., Cameron, A. J., et al. 2025, *arXiv e-prints*, arXiv:2510.06347, doi: [10.48550/arXiv.2510.06347](https://doi.org/10.48550/arXiv.2510.06347)
- Claeyssens, A. 2025, *ApJ*
- Claeyssens, A., Adamo, A., Messa, M., et al. 2025, *MNRAS*, 537, 2535, doi: [10.1093/mnras/staf058](https://doi.org/10.1093/mnras/staf058)
- Crowther, P. A. 2007, *ARA&A*, 45, 177
- de Graaff, A., Brammer, G., Weibel, A., et al. 2025, *A&A*, 697, A189, doi: [10.1051/0004-6361/202452186](https://doi.org/10.1051/0004-6361/202452186)
- de Graaff, A., Rix, H.-W., Carniani, S., et al. 2024, *A&A*, 684, A87, doi: [10.1051/0004-6361/202347755](https://doi.org/10.1051/0004-6361/202347755)
- Eldridge, J. J., Stanway, E. R., Xiao, L., McClelland, L. A. S., & others. 2017, *PASA*, 34, e058, doi: [10.1017/pasa.2017.51](https://doi.org/10.1017/pasa.2017.51)
- Endsley, R., Chisholm, J., Stark, D. P., Topping, M. W., & Whitler, L. 2025, *ApJ*, 987, 189, doi: [10.3847/1538-4357/addc74](https://doi.org/10.3847/1538-4357/addc74)
- Endsley, R., Stark, D. P., Whitler, L., et al. 2023, *MNRAS*, 524, 2312, doi: [10.1093/mnras/stad1919](https://doi.org/10.1093/mnras/stad1919)
- Esteban, C., Bresolin, F., Peimbert, M., et al. 2009, *ApJ*, 700, 654
- Esteban, C., García-Rojas, J., Carigi, L., et al. 2014, *MNRAS*, 443, 624
- Esteban, C., Peimbert, M., Torres-Peimbert, S., & Rodríguez, M. 2002, *ApJ*, 581, 241
- Fujimoto, S., Naidu, R. P., Chisholm, J., & others. 2025, *ApJ*, 989, 46, doi: [10.3847/1538-4357/ade9a1](https://doi.org/10.3847/1538-4357/ade9a1)
- Furtak, L., et al. 2025, *apj*
- Galliano, F., Galametz, M., & Jones, A. P. 2018, *ARA&A*, 56, 673, doi: [10.1146/annurev-astro-081817-051900](https://doi.org/10.1146/annurev-astro-081817-051900)
- García-Rojas, J., & Esteban, C. 2007, *ApJ*, 670, 457
- Garnett, D. R. 1990, *ApJ*, 363, 142
- Garnett, D. R. 1992, *AJ*, 103, 1330
- Garnett, D. R., Shields, G. A., Peimbert, M., et al. 1999, *ApJ*, 513, 168, doi: [10.1086/306860](https://doi.org/10.1086/306860)
- Götberg, Y., de Mink, S. E., Groh, J. H., Leitherer, C., & Norman, C. 2019, *A&A*, 629, A134, doi: [10.1051/0004-6361/201834525](https://doi.org/10.1051/0004-6361/201834525)
- Gunasekera, C. M., van Hoof, P. A. M., Chatzikos, M., & Ferland, G. J. 2023, *Research Notes of the American Astronomical Society*, 7, 246, doi: [10.3847/2515-5172/ad0e75](https://doi.org/10.3847/2515-5172/ad0e75)
- Gunawardhana, M. L. P., Brinchmann, J., Croom, S., et al. 2025, *arXiv e-prints*, arXiv:2504.12584, doi: [10.48550/arXiv.2504.12584](https://doi.org/10.48550/arXiv.2504.12584)
- Harikane, Y., Inoue, A. K., Ellis, R. S., et al. 2025a, *ApJ*, 980, 138, doi: [10.3847/1538-4357/ad9b2c](https://doi.org/10.3847/1538-4357/ad9b2c)
- Harikane, Y., Sanders, R. L., Ellis, R., et al. 2025b, *arXiv e-prints*, arXiv:2505.09186, doi: [10.48550/arXiv.2505.09186](https://doi.org/10.48550/arXiv.2505.09186)
- Harris, C. R., Millman, K. J., van der Walt, S. J., et al. 2020, *Nature*, 585, 357, doi: [10.1038/s41586-020-2649-2](https://doi.org/10.1038/s41586-020-2649-2)
- Hayes, M. J., Saldana-Lopez, A., Citro, A., et al. 2025, *ApJ*, 982, 14, doi: [10.3847/1538-4357/adaea1](https://doi.org/10.3847/1538-4357/adaea1)

- Heintz, K. E., Brammer, G. B., Watson, D., et al. 2025, *A&A*, 693, A60, doi: [10.1051/0004-6361/202450243](https://doi.org/10.1051/0004-6361/202450243)
- Henry, R. B. C., Edmunds, M. G., & Köppen, J. 2000, *ApJ*, 541, 660
- Hsiao, T. Y.-Y., Topping, M. W., Coe, D., et al. 2024, arXiv e-prints, arXiv:2409.04625, doi: [10.48550/arXiv.2409.04625](https://doi.org/10.48550/arXiv.2409.04625)
- Isobe, Y., Ouchi, M., Nakajima, K., et al. 2023, *ApJ*, 956, 139, doi: [10.3847/1538-4357/acf376](https://doi.org/10.3847/1538-4357/acf376)
- Izotov, Y. I., Stasińska, G., Meynet, G., Guseva, N. G., & Thuan, T. X. 2006, *A&A*, 448, 955
- Izotov, Y. I., & Thuan, T. X. 1999, *ApJ*, 511, 639
- . 2007, *ApJ*, 665, 1115
- James, B. L., Auger, M., Aloisi, A., Calzetti, D., & Kewley, L. 2016, *ApJ*, 816, 40, doi: [10.3847/0004-637X/816/1/40](https://doi.org/10.3847/0004-637X/816/1/40)
- James, B. L., Berg, D. A., King, T., et al. 2021, *ApJ*
- Ji, X., Belokurov, V., Maiolino, R., et al. 2025, arXiv e-prints, arXiv:2505.12505, doi: [10.48550/arXiv.2505.12505](https://doi.org/10.48550/arXiv.2505.12505)
- Ji, X., Übler, H., Maiolino, R., et al. 2024, arXiv e-prints, arXiv:2404.04148, doi: [10.48550/arXiv.2404.04148](https://doi.org/10.48550/arXiv.2404.04148)
- Kennicutt, Jr., R. C. 1984, *ApJ*, 287, 116, doi: [10.1086/162669](https://doi.org/10.1086/162669)
- . 1992, *ApJ*, 388, 310, doi: [10.1086/171154](https://doi.org/10.1086/171154)
- Kluyver, T., Ragan-Kelley, B., Pérez, F., et al. 2016, in *Positioning and Power in Academic Publishing: Players, Agents and Agendas*, ed. F. Loizides & B. Schmidt, IOS Press, 87 – 90
- Kobayashi, C., & Ferrara, A. 2024, *ApJL*, 962, L6, doi: [10.3847/2041-8213/ad1de1](https://doi.org/10.3847/2041-8213/ad1de1)
- Kobayashi, C., Karakas, A. I., & Lugaro, M. 2020, *ApJ*, 900, 179, doi: [10.3847/1538-4357/abae65](https://doi.org/10.3847/1538-4357/abae65)
- Kobayashi, C., Umeda, H., Nomoto, K., Tominaga, N., & Ohkubo, T. 2006, *ApJ*, 653, 1145
- Kramarenko, I. G., Rosdahl, J., Blaizot, J., et al. 2025, arXiv e-prints, arXiv:2509.05403, doi: [10.48550/arXiv.2509.05403](https://doi.org/10.48550/arXiv.2509.05403)
- Limongi, M., & Chieffi, A. 2018, *ApJS*, 237, 13, doi: [10.3847/1538-4365/aacb24](https://doi.org/10.3847/1538-4365/aacb24)
- López-Sánchez, Á. R., Esteban, C., García-Rojas, J., Peimbert, M., & Rodríguez, M. 2007, *ApJ*, 656, 168
- Luridiana, V., Morisset, C., & Shaw, R. A. 2015, *A&A*, 573, A42
- Mainali, R., Kollmeier, J. A., Stark, D. P., & others. 2017, *ApJL*, 836, L14
- Maiolino, R., & Mannucci, F. 2019, *A&A Rv*, 27, 3, doi: [10.1007/s00159-018-0112-2](https://doi.org/10.1007/s00159-018-0112-2)
- Maiolino, R., Scholtz, J., Witstok, J., Carniani, S., et al. 2023, arXiv e-prints, arXiv:2305.12492, doi: [10.48550/arXiv.2305.12492](https://doi.org/10.48550/arXiv.2305.12492)
- Markwardt, C. B. 2009, in *Astronomical Society of the Pacific Conference Series*, Vol. 411, *Astronomical Data Analysis Software and Systems XVIII*, ed. D. A. Bohlender, D. Durand, & P. Dowler, 251
- Marques-Chaves, R., Schaerer, D., Kuruvanthodi, A., et al. 2024, *A&A*, 681, A30, doi: [10.1051/0004-6361/202347411](https://doi.org/10.1051/0004-6361/202347411)
- Martinez, Z., Berg, D., James, B., & others. 2025, *ApJ*
- Mason, C. A., Trenti, M., & Treu, T. 2023, *MNRAS*, 521, 497, doi: [10.1093/mnras/stad035](https://doi.org/10.1093/mnras/stad035)
- Massey, P., Neugent, K. F., & Levesque, E. M. 2017, *Philosophical Transactions of the Royal Society of London Series A*, 375, 20160267, doi: [10.1098/rsta.2016.0267](https://doi.org/10.1098/rsta.2016.0267)
- Massey, P., Neugent, K. F., & Morrell, N. 2015, *ApJ*, 807, 81, doi: [10.1088/0004-637X/807/1/81](https://doi.org/10.1088/0004-637X/807/1/81)
- Matthee, J., Mackenzie, R., Simcoe, R. A., & others. 2023, *ApJ*, 950, 67, doi: [10.3847/1538-4357/acc846](https://doi.org/10.3847/1538-4357/acc846)
- Messa, M., Vanzella, E., Loiacono, F., et al. 2025, arXiv e-prints, arXiv:2507.18705, doi: [10.48550/arXiv.2507.18705](https://doi.org/10.48550/arXiv.2507.18705)
- Meynet, G., & Maeder, A. 2005, *A&A*, 429, 581, doi: [10.1051/0004-6361:20047106](https://doi.org/10.1051/0004-6361:20047106)
- Mingozzi, M., Berg, D. A., Chisholm, J., et al. 2022, *ApJ*
- Monna, A., Seitz, S., Greisel, N., & others. 2014, *MNRAS*, 438, 1417, doi: [10.1093/mnras/stt2284](https://doi.org/10.1093/mnras/stt2284)
- Muñoz, J. B., Mirocha, J., Furlanetto, S., & Sabti, N. 2023, *MNRAS*, 526, L47, doi: [10.1093/mnras/slady115](https://doi.org/10.1093/mnras/slady115)
- Nagele, C., & Umeda, H. 2023, *ApJL*, 949, L16, doi: [10.3847/2041-8213/acd550](https://doi.org/10.3847/2041-8213/acd550)
- Naidu, R. P., Oesch, P. A., Brammer, G., et al. 2025, arXiv e-prints, arXiv:2505.11263, doi: [10.48550/arXiv.2505.11263](https://doi.org/10.48550/arXiv.2505.11263)
- Napolitano, L., Castellano, M., Pentericci, L., et al. 2024, arXiv e-prints, arXiv:2410.18763, doi: [10.48550/arXiv.2410.18763](https://doi.org/10.48550/arXiv.2410.18763)
- Neugent, K., & Massey, P. 2019, *Galaxies*, 7, 74, doi: [10.3390/galaxies7030074](https://doi.org/10.3390/galaxies7030074)
- Neugent, K. F., & Massey, P. 2023, *AJ*, 166, 68, doi: [10.3847/1538-3881/ace25f](https://doi.org/10.3847/1538-3881/ace25f)
- Newville, M., Stensitzki, T., Allen, D. B., & Ingargiola, A. 2015, *LMFIT: Non-Linear Least-Square Minimization and Curve-Fitting for Python*, 0.8.0, Zenodo, doi: [10.5281/zenodo.11813](https://doi.org/10.5281/zenodo.11813)
- Nicholls, D. C., Sutherland, R. S., Dopita, M. A., Kewley, L. J., & Groves, B. A. 2017, *MNRAS*, 466, 4403
- Pascale, M., Dai, L., McKee, C. F., & Tsang, B. T. H. 2023, *ApJ*, 957, 77, doi: [10.3847/1538-4357/acf75c](https://doi.org/10.3847/1538-4357/acf75c)
- Peña-Guerrero, M. A., Leitherer, C., de Mink, S., Wofford, A., & Kewley, L. 2017, *ApJ*, 847, 107
- Pérez-Montero, E., Amorín, R., Sánchez Almeida, J., et al. 2021, *MNRAS*, 504, 1237, doi: [10.1093/mnras/stab862](https://doi.org/10.1093/mnras/stab862)
- Pérez-Montero, E., & Contini, T. 2009, *MNRAS*, 398, 949
- Pilyugin, L. S., & Thuan, T. X. 2005, *ApJ*, 631, 231
- Rémy-Ruyer, A., Madden, S. C., Galliano, F., et al. 2014, *A&A*, 563, A31, doi: [10.1051/0004-6361/201322803](https://doi.org/10.1051/0004-6361/201322803)
- Rivera-Thorsen, T. E., Chisholm, J., Welch, B., et al. 2024, *A&A*, 690, A269, doi: [10.1051/0004-6361/202450359](https://doi.org/10.1051/0004-6361/202450359)
- Rogers, N. S. J., Skillman, E. D., Pogge, R. W., et al. 2022, *ApJ*, 939, 44, doi: [10.3847/1538-4357/ac947d](https://doi.org/10.3847/1538-4357/ac947d)

- Roman-Duval, J., Jenkins, E. B., Tchernyshyov, K., et al. 2022, *ApJ*, 928, 90, doi: [10.3847/1538-4357/ac5248](https://doi.org/10.3847/1538-4357/ac5248)
- Roy, J.-R., & Kunth, D. 1995, *A&A*, 294, 432
- Sander, A. A. C., Vink, J. S., & Hamann, W. R. 2020, *MNRAS*, 491, 4406, doi: [10.1093/mnras/stz3064](https://doi.org/10.1093/mnras/stz3064)
- Schaerer, D., Marques-Chaves, R., Xiao, M., & Korber, D. 2024, *A&A*, 687, L11, doi: [10.1051/0004-6361/202450721](https://doi.org/10.1051/0004-6361/202450721)
- Schmidt, K. B., Huang, K.-H., Treu, T., et al. 2017, *ApJ*, 839, 17
- Senchyna, P., Plat, A., Stark, D. P., & Rudie, G. C. 2023, *arXiv e-prints*, arXiv:2303.04179, doi: [10.48550/arXiv.2303.04179](https://doi.org/10.48550/arXiv.2303.04179)
- Senchyna, P., Stark, D. P., Vidal-García, A., et al. 2017, *MNRAS*, 472, 2608
- Shirazi, M., & Brinchmann, J. 2012, *MNRAS*, 421, 1043
- Simmonds, C., Tacchella, S., McClymont, W., et al. 2025, *arXiv e-prints*, arXiv:2508.04410, doi: [10.48550/arXiv.2508.04410](https://doi.org/10.48550/arXiv.2508.04410)
- Stark, D. P., Topping, M. W., Endsley, R., & Tang, M. 2025, *arXiv e-prints*, arXiv:2501.17078, doi: [10.48550/arXiv.2501.17078](https://doi.org/10.48550/arXiv.2501.17078)
- Stasińska, G., & Schaerer, D. 1997, *A&A*, 322, 615, doi: [10.48550/arXiv.astro-ph/9611067](https://doi.org/10.48550/arXiv.astro-ph/9611067)
- Sun, G., Faucher-Giguère, C.-A., Hayward, C. C., et al. 2023, *ApJL*, 955, L35, doi: [10.3847/2041-8213/acf85a](https://doi.org/10.3847/2041-8213/acf85a)
- Topping, M. W., Sanders, R. L., Shapley, A. E., et al. 2025a, *arXiv e-prints*, arXiv:2502.08712, doi: [10.48550/arXiv.2502.08712](https://doi.org/10.48550/arXiv.2502.08712)
- Topping, M. W., Stark, D. P., Senchyna, P., & others. 2025b, *ApJ*, 980, 225, doi: [10.3847/1538-4357/ada95c](https://doi.org/10.3847/1538-4357/ada95c)
- Topping, M. W., Stark, D. P., Senchyna, P., et al. 2024, *MNRAS*, 529, 3301, doi: [10.1093/mnras/stae682](https://doi.org/10.1093/mnras/stae682)
- Tosi, M. 1988, *A&A*, 197, 33
- Usui, M., Mawatari, K., Álvarez-Márquez, J., et al. 2025, *ApJL*, 991, L38, doi: [10.3847/2041-8213/ae0574](https://doi.org/10.3847/2041-8213/ae0574)
- Valentino, F., Heintz, K. E., Brammer, G., et al. 2025, *A&A*, 699, A358, doi: [10.1051/0004-6361/202553908](https://doi.org/10.1051/0004-6361/202553908)
- van Zee, L., & Haynes, M. 2006, *ApJ*, 636, 214
- Vincenzo, F., Miglio, A., Kobayashi, C., Mackereth, J. T., & Montalbán, J. 2019, *A&A*, 630, A125, doi: [10.1051/0004-6361/201935886](https://doi.org/10.1051/0004-6361/201935886)
- Vink, J. S. 2023, *A&A*, 679, L9, doi: [10.1051/0004-6361/202347827](https://doi.org/10.1051/0004-6361/202347827)
- Watanabe, K., Ouchi, M., & Nakajima, K. o. 2024, *ApJ*, 962, 50, doi: [10.3847/1538-4357/ad13ff](https://doi.org/10.3847/1538-4357/ad13ff)