Early Results from GLASS-JWST. IV. Spatially Resolved Metallicity in a Low-mass $z \sim 3$ Galaxy with NIRISS*

Xin Wang1,2,3, Tucker Jones4, Benedetta Vulcain5, Tommaso Treu6, Takahiro Morishita3, Guido Roberts-Borsani6, Matthew A. Malkan6, Alaina Henry7,8, Gabriel Brammer9,10, Victoria Straat9,10, Maruša Bradac4,11,12, Kristian Boyett12,13, Antonello Calabrò14, Marco Castellano14, Adriano Fontana14, Karl Glazebrook15, Patrick L. Kelly16, Nicha Leethochawalit12,13,14, Danilo Marchesini18, and Lilan Yang18

1 School of Astronomy and Space Science, University of Chinese Academy of Sciences
2 National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, People’s Republic of China
3 Infrared Processing and Analysis Center, Caltech, 1200 E. California Boulevard, Pasadena, CA 91125, USA
4 Department of Physics and Astronomy, University of California Davis, 1 Shields Avenue, Davis, CA 95616, USA
5 INAF Osservatorio Astronomico di Padova, vicolo dell’Osservatorio 5, 35122 Padova, Italy
6 Department of Physics and Astronomy, University of California, Los Angeles, 430 Portola Plaza, Los Angeles, CA 90095, USA
7 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore MD 21218, USA
8 Center for Astrophysical Sciences, Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA
9 Cosmic Dawn Center (DAWN), Denmark
10 Niels Bohr Institute, University of Copenhagen, Jagtvej 128, DK-2200 Copenhagen N, Denmark
11 University of Ljubljana, Department of Mathematics and Physics, Jadranska ulica 19, SI-1000 Ljubljana, Slovenia
12 School of Physics, University of Melbourne, Parkville 3010, VIC, Australia
13 ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), Australia
14 INAF Osservatorio Astronomico di Roma, Via Frascati 33, I-00078 Monteporzio Catone, Rome, Italy
15 Centre for Astrophysics and Supercomputing, Swinburne University of Technology, PO Box 218, Hawthorn, VIC 3122, Australia
16 School of Physics and Astronomy, University of Minnesota, 116 Church Street SE, Minneapolis, MN 55455, USA
17 National Astronomical Research Institute of Thailand (NARIT), Mae Rim, Chiang Mai, 50180, Thailand
18 Department of Physics and Astronomy, Tufts University, 574 Boston Avenue, Medford, MA 02155, USA
19 Kavli Institute for the Physics and Mathematics of the Universe, The University of Tokyo, Kashiwa, 277-8583, Japan

Abstract

We report the first gas-phase metallicity map of a distant galaxy measured with the James Webb Space Telescope (JWST). We use the NIRISS slitless spectroscopy acquired by the GLASS Early Release Science program to spatially resolve the rest-frame optical nebular emission lines in a gravitationally lensed galaxy at $z = 3.06$ behind the A2744 galaxy cluster. This galaxy (dubbed GLASS-Zgrad1) has stellar mass $\sim 10^{10} M_\odot$, instantaneous star formation rate $\sim 6.6 M_\odot$ yr$^{-1}$ (both corrected for lensing magnification), and global metallicity one-fourth solar. From its emission-line maps ([O III], Hβ, Hα, [Ne iii], and [O ii]), we derive its spatial distribution of gas-phase metallicity using a well-established forward-modeling Bayesian inference method. The exquisite resolution and sensitivity of JWST/NIRISS, combined with lensing magnification, enable us to resolve this $z \sim 3$ dwarf galaxy in $\sim 50$ resolution elements with sufficient signal, an analysis hitherto not possible. We find that the radial metallicity gradient of GLASS-Zgrad1 is strongly inverted (i.e., positive): $\Delta \log([O II]/H\alpha) / \Delta r = 0.165 \pm 0.023$ dex kpc$^{-1}$. This measurement is robust at $\Delta r > 4 \sigma$ confidence level against known systematics. This positive gradient may be due to tidal torques induced by a massive nearby galaxy, which can cause inflows of metal-poor gas into the central regions of GLASS-Zgrad1. These first results showcase the power of JWST wide-field slitless spectroscopic maps to resolve the mass assembly and chemical enrichment of low-mass galaxies in and beyond the peak epoch of cosmic star formation ($z \gtrsim 2$). Reaching masses $\lesssim 10^9 M_\odot$ at these redshifts is especially valuable to constrain the effects of galactic feedback and environment and is possible only with JWST’s new capabilities.

Unified Astronomy Thesaurus concepts: Galaxy abundances (574); Galaxy evolution (594); Galaxy formation (595); High-redshift galaxies (734); Strong gravitational lensing (1643)

1. Introduction

A central challenge in galaxy evolution is to understand how galaxies assemble their baryonic mass and cycle their gas and heavy elements in and around themselves. Deep imaging and spectroscopic surveys with the Hubble Space Telescope (HST), the Sloan Digital Sky Survey (SDSS), and other facilities have provided a census of the cosmic star formation rate (SFR) and hence metal enrichment history, which peak at $1 \lesssim z \lesssim 3$ (the “cosmic noon” epoch; e.g., Madau & Dickinson 2014). Dedicated observational campaigns have established tight correlations among various physical properties of star-forming galaxies at this epoch, e.g., stellar mass ($M_*$), SFR, gas-phase metallicity, size, morphology, kinematics, and dust and gas content (see recent reviews by Kewley et al. 2019; Maiolino & Mannucci 2019). These integrated scaling relations are largely reproduced by theoretical semianalytic models and simulations.

* Based on observations acquired by the JWST under the ERS program ID 1324 (PI T. Treu).

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that incorporate accretion and merging, star formation, and feedback in the form of gaseous outflows powered by star formation and supermassive black hole accretion (e.g., Somerville and Davé 2015). However, key properties of galactic outflows such as their mass-loss rates and recycling timescales, have proven extremely challenging to discern, especially at intermediate and high redshifts. A variety of assumptions and “subgrid” physical models are able to reproduce global galaxy scaling relations. Hence, additional observational constraints are needed to better understand how feedback redistributes baryons within and around galaxies.

Gas-phase metallicity gradients are sensitive probes of the complex gas flows driven by galactic feedback and tidal interactions. The value of gas metallicity maps as a diagnostic of galaxy formation has been demonstrated by numerous integral field spectroscopy (IFS) surveys at z = 0 (e.g., Sanchez et al. 2014; Belfiore et al. 2017; Poelodjojo et al. 2018; Franchetto et al. 2021). Theoretical models and simulations make differing predictions for metallicity gradient evolution, depending on the strength of feedback and the outflow properties at high redshifts (Gibson et al. 2013). Predictions diverge the most at low stellar masses (\(M_* \lesssim 10^9 M_\odot\)), especially at \(z > 2\) (Gibson et al. 2013; Mott et al. 2013; Molla et al. 2019; Hemler et al. 2021). This is a key regime where feedback may be important for dynamical evolution and is even a candidate to resolve the longstanding “cusp-core” problem (and related challenges to the cold dark matter paradigm; e.g., Bullock & Boylan-Kolchin 2016). However, observations are challenging due to the small angular sizes of high-z galaxies, and ground-based adaptive optics studies have yielded limited samples (e.g., Jones et al. 2013; Yuan et al. 2013; Leethochawalit et al. 2016; Curti et al. 2020). Meanwhile, HST grism surveys have made substantial progress in charting resolved chemical enrichment at high redshifts (Jones et al. 2015; Wang et al. 2017, 2020; Simons et al. 2021; Li et al. 2022). Combining WFC3 grism spectroscopy with gravitational lensing magnification, Wang et al. (2020) assembled a large sample of galaxies with sub-kpc (subkiloparsec) resolution metallicity radial gradients at cosmic noon. While this progress is encouraging, results from HST are limited by wavelength coverage to \(z \lesssim 2.3\) and typically probe \(M_* \gtrsim 10^9 M_\odot\).

The Near-infrared Imager and Slitless Spectrograph (NIRISS; Willott et al. 2022) on board the James Webb Space Telescope (JWST) now enables a tremendous leap forward with its superior sensitivity, angular resolution, and longer-wavelength coverage compared to HST/WFC3. This allows resolved metallicity studies probing higher redshifts and lower-mass galaxies, which are a powerful discriminant of feedback and outflow models (e.g., Ma et al. 2017; Hemler et al. 2021). This Letter presents the first study of gas-phase metallicity maps at \(z > 3\), a regime not yet explored observationally, based on the NIRISS data acquired by the Early Release Science (ERS) program GLASS-JWST (ID ERS-1324; Treu et al. 2022). These observations also take advantage of the gravitational lensing magnification by the galaxy cluster A2744 to study background high-z sources in high definition.

This Letter is structured as follows. We briefly describe the observations in Section 2. In Section 3 we describe the extraction of emission-line maps and subsequent measurements of gas-phase metallicity (both the global value and spatial map). We discuss the results in Section 4 and summarize the main conclusions in Section 5. We adopt a standard cosmology with \(\Omega_m = 0.3\), \(\Omega_L = 0.7\), and \(H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1}\), and a Chabrier (2003) initial mass function (IMF).

2. Observations

In this Letter, we use JWST/NIRISS data from GLASS-ERS, whose observing strategy is described by Treu et al. (2022), and data reduction in Paper I (Roberts-Borsani et al. 2022). In brief, the A2744 cluster core was observed for \(\sim 15\) hr with NIRISS wide-field slitless spectroscopy and direct imaging in three filters (F115W, F150W, and F200W). This provides low-resolution \(R \sim 150\) spectra of all objects in the field of view with continuous wavelength coverage from \(\lambda \in [1.0, 2.2]\) \(\mu\text{m}\) (rest-frame \([0.24, 0.54]\) \(\mu\text{m}\) at \(z = 3.06\)). This includes the strong rest-frame optical emission lines [Mg II], [O II], [Ne III], H\(_\gamma\), H\(_\beta\), and [O III]. Spectra are taken at two orthogonal dispersion angles (using the GR150C and GR150R grism elements), which helps to minimize the effects of contamination by overlapping spectral traces.

3. Data Analysis

Here we focus on the NIRISS observations of one galaxy (GLASS-Zgrad1) at \(z = 3.06\), whose measured properties are given in Table 1. GLASS-Zgrad1 has a highly secure grism redshift determination given by GRIZLI, with \((\Delta z)_\text{posterior}/(1+z_{\text{peak}}) = 1.7 \times 10^{-4}\), ascribed to its extremely strong rest-frame optical emission lines. Its data benefit from low contamination from neighboring sources, so its spectrum is suitable for measuring emission-line maps. The synergy between JWST’s resolving power and its lensing magnification (estimated to be \(\sim 3\), Johnson et al. 2014; Wang et al. 2015; Bergamini et al. 2022) reveals its detailed physical properties on scales as small as \(\sim 200\) pc. These characteristics make our target a textbook case to showcase the capabilities of JWST in spatially resolving the properties of high-z galaxies. The upper-left panel of Figure 1 shows its color composite image, made by combining the three NIRISS filters (F115W, F150W and F200W). The galaxy shows a smooth light profile, with no clear signs of clumpy structures. The location of GLASS-Zgrad1 on the mass–excitation diagram (Juneau et al. 2014; Coil et al. 2015) indicates negligible emission-line contamination from an active galactic nucleus (AGN), such that we can apply standard gas-phase metallicity diagnostics for H\(_\text{II}\) regions.

While GLASS-Zgrad1 itself shows no clear signs of interaction, it is located only \(\sim 15\) kpc in projection from a \(\sim 100\times\) more massive galaxy (\(M_* \approx 10^{10.6} M_\odot\)) at a consistent redshift (Sun et al. 2022; Wu et al. 2022). This massive companion shows a potentially spiral structure that may be induced by interaction with GLASS-Zgrad1 (Wu et al. 2022). Such interaction may affect the metallicity gradient via torques on the gas; we discuss this possibility in Section 4.

3.1. Emission-line Map and Metallicity Measurements

We rely on the latest version the Grism Redshift & Line software (GRIZLI; Brammer & Matharu 2021) to extract and

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20 https://www.stsci.edu/jwst/science-execution/approved-programs/dders/program-1324
21 https://github.com/gbrammer/grizli
We jointly constrain the ionized gas metallicities (12 + log(O/H)), nebular dust extinction (A_N), and dereddened Hβ line flux (f_{Hβ}) using our forward-modeling Bayesian inference method, largely described in Wang et al. (2017, 2019, 2020, 2022). The likelihood function is defined as

\[
  L \propto \exp \left( -\frac{1}{2} \sum_i \left( \frac{f_{\text{EL}_i} - R_i \cdot f_{\text{H} \beta}}{\sigma_{\text{EL}_i}} \right)^2 + \left( \frac{f_{\text{H} \beta}}{\sigma_{R_i}} \right)^2 \right)
\]

where f_{\text{EL}_i} and \sigma_{\text{EL}_i} represent the dereddened emission-line (e.g., [O II], Hγ, Hβ, [O III]) flux and its uncertainty (measured from the flux-calibrated error array; see Roberts-Borsani et al. 2022), corrected using the Calzetti et al. (2000) dust extinction law with A_v as a free parameter. R_i = f_{\text{EL}_i}/f_{\text{H} \beta} is the expected flux ratio of each line with respect to H β, based on the adopted metallicity calibrations and intrinsic Balmer decrements, while \sigma_R is the intrinsic scatter in R_i. To compute metallicity, we adopt the purely empirical strong line diagnostics described by Bian et al. (2018), calibrated against a sample of local analogs of high-z galaxies according to their location on the BPT (Baldwin et al. 1981) diagram. We note that the dust extinction A_N is constrained by the metallicity diagnostics in addition to H Balmer line ratios, as described in our earlier work. For example, the characteristic locus of R_{23} versus O_32 (see, e.g., Shapley et al. 2015) and the intrinsic [O III]/[Ne III] line ratios (Jones et al. 2015) provide constraints on A_N along with traditional diagnostics such as H β/Hγ. The effect of uncertainty in A_N is included in our metallicity uncertainties. To estimate the instantaneous star formation rate (SFR), we use the Balmer line luminosity assuming the Kennicutt (1998) calibration scaled to the Chabrier (2003) IMF, i.e., SFRN = 1.6 × 10^{-42} \frac{L(H)}{\text{[erg s}^{-1}\text{]}} [M_\odot \text{yr}^{-1}].

The forward-modeling Bayesian inference described above is first performed on the integrated emission-line fluxes to yield global values of 12 + log(O/H), A_N, and SFR (with results listed in Table 1). We then utilize Voronoi tessellation (Cappellari & Copin 2003; Diehl & Statler 2006) as in Wang et al. (2019, 2020) to construct spatial bins with nearly uniform signal-to-noise ratios (S/Ns) of [O III], the strongest emission line available. We apply the Bayesian inference with line fluxes in each Voronoi bin, yielding maps of metallicity and other properties at sub-kpc resolution. Overall, we are able to resolve this z ∼ 3 dwarf galaxy with S/N > 50 resolution elements at an S/N threshold of 10 in [O III].

As this work relies on emission lines spanning multiple spectrophotometric filters, we have examined the relative flux calibration accuracy as a potential source of error. Comparing the spectra with both broadband photometric colors and best-fit spectral templates, we estimate that the relative calibration is accurate to within ±10% near the center of each filter (F115W, F150W, and F200W). This applies to the strong lines of [O II], [Ne III], Hβ, and [O III] in our z = 3.06 target. Calibration uncertainty for [Ne III]/[O II] and [O III]/Hβ appears to be negligible. However, fluxes near band edges appear to be underestimated in some cases, possibly due to the slight misalignment of the expected and actual spectral trace positions. This potentially affects the Hγ line such that its true flux may be ∼20% larger than we report here. We note that the systematic error of this magnitude is smaller than the statistical uncertainty for spatial Voronoi bins (where line ratio uncertainties are >10% and Hγ is undetected). Any relative calibration error between the F150W and F200W spectra would appear similar to a change in A_v; in this case, our methodology would produce a bias in A_v but not in 12 + log(O/H).

### Table 1

| Galaxy | Physical Properties of Galaxy GLASS-Zgrad1 |
|--------|------------------------------------------|
|        | R.A. (deg) | Decl. (deg) | \(z_{\text{spec}}\) | \(\mu\) | GLASS-Zgrad1 |
|        | 3.585943 | -30.382102 | 3.06 | 3.00 | 10.03 |
|        |          |            |          |        |          |
|        | Observed Emission-line Fluxes |            |          |        |          |
|        | \(f_{\text{[O}]0} \) [10^{-19}ergs cm^{-2} s^{-1}] | 913.77 ± 6.95 |
|        | \(f_{\text{H} \beta} \) [10^{-19}ergs cm^{-2} s^{-1}] | 161.68 ± 8.89 |
|        | \(f_{\text{H} \alpha} \) [10^{-19}ergs cm^{-2} s^{-1}] | 40.71 ± 12.73 |
|        | \(f_{\text{[Ne]}} \) [10^{-19}ergs cm^{-2} s^{-1}] | 101.65 ± 14.76 |
|        | \(f_{\text{[O]}} \) [10^{-19}ergs cm^{-2} s^{-1}] | 207.43 ± 6.95 |
|        | Rest-frame Equivalent Widths |            |          |        |          |
|        | \(\text{EW}_{\text{[O]}} \) [Å] | 749.37 ± 25.23 |
|        | \(\text{EW}_{\text{H} \beta} \) [Å] | 156.92 ± 10.18 |
|        | \(\text{EW}_{\text{H} \alpha} \) [Å] | 31.66 ± 9.39 |
|        | \(\text{EW}_{\text{[Ne]}} \) [Å] | 47.80 ± 6.51 |
|        | \(\text{EW}_{\text{[O]}} \) [Å] | 130.52 ± 6.70 |
|        | Nebular Emission Diagnostics |            |          |        |          |
|        | \(12 + \log(O/H)_{\text{global}} \) | 8.11 ± 0.16 |
|        | \(\Delta \log(O/H) / \Delta r \) [dex kpc^{-1}] | 0.165 ± 0.023 |
|        | SFRN [M_\odot yr^{-1}] | 8.64 ± 0.48 |
|        | \(\log (\text{SFR}/[\text{yr}^{-1}]) \) | -7.68 ± 0.22 |
|        | \(A_N \) | 0.54 ± 0.03 |
|        | Broadband Photometry SED Fitting |            |          |        |          |
|        | \(\log (M_\odot / M_{\text{sed}}) \) | 8.62 ± 0.07 |
|        | SFR [M_\odot yr^{-1}] | 4.28 ± 0.04 |
|        | \(\log (\text{SFR} / [\text{yr}^{-1}]) \) | -7.97 ± 0.10 |
|        | \(A_v \) | 0.60 ± 0.03 |
|        | Note: The values of \(M_\odot \) and SFR have been corrected for lensing magnification. |
Figure 1. Galaxy GLASS-Zgrad1, a $z \sim 3$ star-forming dwarf galaxy ($M_\star \approx 10^8 M_\odot$) with a strongly inverted metallicity radial gradient presented in this work: the first metallicity map obtained with the JWST and the first-ever such measurement secured by sufficient spatial resolution ($\leq$pkc) at $z \geq 3$. Top, from left to right: the color composite stamp (made using the three-band JWST/NIRISS pre-imaging on a 30 mas plate scale), stellar surface density ($\Sigma_*$) map (derived from the pixel-by-pixel SED fitting), and surface-brightness maps of emission lines ([O II], H$\gamma$, H$\beta$ and [O III]), measured from the NIRISS slitless spectroscopy acquired by GLASS-JWST. The black contours mark the delensed deprojected galactocentric radii with a 1 kpc interval, given by our source-plane morphological reconstruction using the public lens model. The orientation (north up and east to the left) and spatial extent remain unchanged throughout all the 2D maps. Middle: the optimally extracted 1D observed $F_\lambda$ flux and its 1$\sigma$ uncertainty, represented by the blue solid lines and cyan shaded bands, respectively, combined from the two orthogonal dispersion directions (GR150C and GR150R). In total, the exposure time per filter combined from both dispersions reaches 2.9 hr. The forward-modeled spectra (source continuum + nebular emission), based on the best-fit intrinsic SED with source morphological broadening taken into account, is shown in the red dashed line. Bottom: the continuum-subtracted 2D grism spectra covered by the three filters (F115W, F150W, and F200W), respectively, showcasing the quality of our GLASS-JWST slitless spectroscopy.

3.2. SED Fitting and Stellar-mass Map

There has been a wealth of deep multiwavelength imaging in broad bands covering 0.2–5 $\mu$m wavelengths in the field of A2744. We rely on the photometric catalog compiled by the ASTRODEEP project (Merlin et al. 2016), which performs aperture-matched and blending-corrected photometry of the HFF seven-band, Hawk-I KS, and Spitzer IRAC images (Brammer et al. 2016; Lotz et al. 2017). We use the BAGPIPES software (Carnall et al. 2018) to fit the BC03 models (Bruzual & Charlot 2003) of galaxy spectral energy distributions (SEDs) to the ASTRODEEP photometry. BAGPIPES is capable of adding the nebular emission component into galaxy spectra, so the emission-line fluxes are taken into account in the fit simultaneously. Basic assumptions and parameter ranges include the Chabrier (2003) IMF, a stellar metallicity range of $Z/Z_\odot \in (0, 2.5)$, the Calzetti et al. (2000) dust extinction law with $A_\beta$ in the range of $(0, 3)$, and an exponentially declining star formation history with $\tau$ in the range of $(0.01, 10)$Gyr. We fix the spectroscopic redshift of our galaxy to its best-fit grism value ($z = 3.06$), with a conservative uncertainty of $\pm 0.003$, following Momcheva et al. (2016). The obtained physical properties are presented in Table 1. The measured stellar mass and SFR$^\mathrm{d}$ are log($M_\star/M_\odot$) = 8.62$^{+0.07}_{-0.10}$ and SFR$^\mathrm{d}$ = 4.28$^{+0.43}_{-0.44}$, respectively, indicating that our galaxy lies 0.14 dex above the star-forming main sequence (Speagle et al. 2014). We also note that our derived values of the dust reddening for the nebular and stellar component are consistent with $E(B - V)^\mathrm{stars} \sim E(B - V)^\mathrm{gas}$ (Reddy et al. 2015).

Broadband image morphology is not necessarily a good tracer of the underlying stellar-mass distribution in star-forming galaxies (e.g., Wuyts et al. 2012). We, therefore, construct stellar-mass maps using spatially resolved SED fitting. We use the same method as Wang et al. (2020), applied to Hubble Frontier Field imaging (Lotz et al. 2017). The F606W, F814W, F105W, F125W, F140W, and F160W HST images are used for this analysis. F435W is not used as it corresponds to the Ly$\alpha$ forest region at $z = 3.06$. Images from each filter are aligned and convolved to a common angular resolution of $0.06$ FWHM, ensuring good sensitivity at low surface brightness reaching beyond the effective radius. The photometry in each $0.06$ square pixel is then fit using FAST (Kriek et al. 2009).
with an exponentially declining star formation history, Chabrier (2003) IMF, and Bruzual & Charlot (2003) stellar population synthesis models (for full details, see Wang et al. 2020). The resulting stellar-mass map is shown in Figure 1. We fit the stellar-mass map with a 2D elliptical Gaussian in order to determine the galactocentric radius at each point (Jones et al. 2015). The stellar-mass surface density is indeed smoother than the luminosity distribution, and we consider morphological parameters based on this mass map to be more reliable.

Future JWST photometry with NIRCam, especially in filters relatively unaffected by strong nebular emission, will enable improved SED-fitting results via spatially resolved photometry at longer wavelengths. Our spatial SED fitting is currently based on HST photometry sampling only ≲4100 Å in the rest frame. NIRISS F200W imaging would extend the wavelength coverage, but it contains strong emission lines that account for ~55% of the total broadband flux based on the Hβ and [O III] equivalent widths. While this can be corrected using the emission-line maps (Figure 1), the effect of including this additional photometry is small and comparable to the uncertainty. We therefore do not use it for this initial study.

3.3. Source-plane Morphology

We perform a source-plane reconstruction of GLASS-Zgrad1 to recover its intrinsic morphology based on a public lens models (Johnson et al. 2014; Wang et al. 2015; Bergamini et al. 2022). Each pixel in the image-plane stellar-mass map is ray-traced back to its source-plane position based on the deflection fields from the macroscopic cluster lens model. We then fit a 2D Gaussian profile to the galaxy’s intrinsic stellar-mass spatial map to pinpoint its axis ratio, orientation, and inclination, so that we obtain the intrinsic source morphology (corrected for lensing distortion). The centroid of this 2D fit is adopted as the galaxy center (r = 0). As a result, we establish the delensed deprojected galactocentric distance scale for each Voronoi bin, as displayed by the black contours in Figures 1 and 2.

4. The First Metallicity Map from JWST/NIRISS Wide-field Slitless Spectroscopy

Here we present the main results of our analysis. The top panels of Figure 1 show the maps of the most prominent emission lines of GLASS-Zgrad1: [O II], Hγ, Hβ, and [O III]. Its optimally extracted 1D spectrum, covered by all three grism filters (F115W, F150W, and F200W) combined from both dispersion elements (GR150C and GR150R), is shown in the central row, while the continuum-subtracted 2D grism spectrum is shown in the bottom row. All nebular emission features used in this work are clearly seen. This 1D/2D spectrum showcases the quality of our NIRISS spatially resolved spectroscopy of high-z emission-line galaxies.

The emission-line maps unveil how most of the emission is concentrated in the galaxy core, sharply decreasing at radii >1 kpc. In the outskirts, the emission looks quite smooth, especially for [O III]. The only exception is Hγ, which appears patchy due to the lower S/N of this line.

Figure 2 shows the 2D metallicity map of GLASS-Zgrad1. We note that variations in the derived metallicity result directly from the intrinsic emission-line flux ratios via Equation (1) (e.g., as shown for the R23 and O32 indices for two examples in Figure 2 of Wang et al. 2019). Clearly, the galaxy outskirts on average display highly elevated metallicities, i.e., more metal-enriched by ~0.2 dex than the center. To quantify the radial gradient, we conduct a linear regression using a simple least-squares method, with the functional form 12 + log(O/H) = θ0 + θ1r. Here, θ0 and θ1 are the radial gradient and the intercept, respectively, and r is the source-plane galactocentric radius in kiloparsecs. We obtain the best-fit and 1σ uncertainty results as θ0 = −0.029 ± 0.023 dex kpc−1 and θ1 = 0.14 ± 0.003 dex kpc−1. The central metallicity is roughly one-third of the solar value (adopting solar 12 + log(O/H) = 8.69; Asplund et al. 2009) with a significant positive radial gradient.

The positive metallicity gradient in GLASS-Zgrad1 is even steeper than those measured by Wang et al. (2019) for two similarly low-mass z ~ 2 galaxies, which also show extremely high emission-line equivalent widths and which have gradients of ~0.1 dex/kpc.

We performed several tests to verify that the positive gradient slope is robust against potential systematic errors. First, we have binned the data in radial annuli to obtain a gradient measurement that is independent of the Voronoi tessellation. Using radial bin sizes such that each has S/N > 10 in [O III], we find θ1 = 0.14 ± 0.03 dex kpc−1, which is fully consistent with our fiducial result (see also similar tests in...
Wang et al. 2017). Second, we consider whether spurious noise features could bias the results. The largest possible effect is from the highest-metallicity region, which is also at the largest radius ($r \approx 2$ kpc). Repeating the analysis with this point removed still results in a significant positive gradient $\theta_1 = 0.076 \pm 0.019$ dex kpc$^{-1}$, albeit smaller than our fiducial result by design. Third, we vary the galaxy center position $M_{\text{AMMOTH-Grism survey}}$.

In Figure 3, we show the redshift evolution of radial metallicity gradients in high-$z$ galaxies secured with sub-kpc spatial resolution. This sub-kpc resolution is crucial in ensuring the results are robust against beam-smearing effects (e.g., Yuan et al. 2013). The vast majority of the galaxies shown here reside in blank fields, with the exceptions of those identified by the MAMMOTH-Grism survey (HST-GO-16276; P.I. Wang; Li et al. 2022) using color-coded circles with maroon edges. In comparison, we show the predictions made by state-of-the-art cosmological hydrodynamic simulations: the $1\sigma$ spread of FIRE (Ma et al. 2017) and Illustris-TNG50 (Hemler et al. 2021), as well as two Milky Way analogs with normal and enhanced feedback strengths but otherwise identical numerical setups (corresponding to MUGS and MaGICC, respectively; Gibson et al. 2013). Despite the wide differences among the numerical recipes implemented, these simulations make indistinguishable predictions at $z \lesssim 1$. However, their predictions diverge more significantly at higher redshifts, leaving a potential breakthrough at $z \gtrsim 2.6$, where the JWST spatially resolved spectroscopy can be highly efficient in deriving metallicity gradients and thus test these theoretical predictions.
cosmological hydrodynamic simulations—FIRE (Ma et al. 2017), Illustris-TNG50 (Hemler et al. 2021), MUGS, and MaGICC (Gibson et al. 2013)—significantly diverge at high redshifts, as a consequence of diverse feedback prescriptions. They also struggle to reproduce the fraction of inverted (positive slope) gradients currently observed.

The existence of a relatively steep positive metallicity gradient in GLASS-Zgrad1 is at first surprising, given the predominately flat or moderately negative radial gradients in Figure 3. However, GLASS-Zgrad1 has a massive companion that may be gravitationally interacting (Section 3; Wu et al. 2022). Such an interaction can induce torques on the gas, causing metal-poor gas at large radii to lose angular momentum and migrate toward the center of the galaxy. This process can result in flattened or inverted metallicity gradients (e.g., Kewley et al. 2006). Indeed, close gravitational interaction is the primary driver of positive gradients in $z \simeq 0$ galaxies (e.g., Rupke et al. 2010; Torrey et al. 2012). We therefore consider it likely that the gradient in our target is indeed steeply positive and is induced by interaction with the nearby object.

In Figure 4, we show the metallicity gradients of these field galaxies in terms of their $M_\star$. This correlation is highly sensitive to galactic feedback. For instance, the two suites of EAGLE simulations using different feedback prescriptions predict widely dissimilar mass dependence (Tissera et al. 2019). Observationally there is considerable scatter in the metallicity gradient slopes, which the current state-of-the-art numerical hydrodynamic simulations (e.g., Ma et al. 2017; Hemler et al. 2021) struggle to reproduce (but see Tissera et al. 2021).

Recently, there has been growing evidence for the existence of inverted metallicity gradients in distant galaxies (Cresci et al. 2010; Wang et al. 2019; Li et al. 2022). Wang et al. (2019) interpreted this phenomenon as an indication of the metal-enriched gas outflows triggered by central starbursts that disrupt galaxies out of equilibrium (also see Sharda et al. 2021), whereas other groups have suggested centrally directed low-metallicity gas infall as the physical cause (Cresci et al. 2010; Mott et al. 2013). The latter scenario has been adopted to explain the inverted gradients observed in protocluster environments where gas inflows are easily drawn by the underlying large gravitational potentials (Li et al. 2022). Here our analysis confirms a third scenario where strongly inverted gradients at high redshifts can be caused by the inflow of metal-poor gas into inner disks as a result of close gravitational interactions. Furthermore, as shown in Figures 3 and 4, the magnitude of the positive radial slope measured in GLASS-Zgrad1 is significantly more dramatic than the sample median of $0.014 \pm 0.022 \text{dex kpc}^{-1}$ measured in the MAMMOTH-Grism galaxies residing in extreme overdensities (Li et al. 2022). This likely suggests that gravitational interactions impose stronger environmental effects on the chemical profiles of high-$z$ galaxies than large-scale overdensities.

5. Conclusions

In this Letter, we present the first spatially resolved analysis of a high-$z$ emission-line galaxy using the wide-field slitless
spectroscopic modes provided by JWST. We first showcase the quality of our NIRISS grism data acquired by the GLASS-JWST-ERS program, presenting the extracted and cleaned 1D/2D grism spectra of a z ~ 3 dwarf galaxy, GLASS-Zgrad1. Via SED fitting to the broadband photometry fully covering its rest-frame UV through optical spectrum, we obtain log(M*/M⊙) = 8.62+0.07−0.10 and SFR = 4.28+0.43−0.44 (M⊙ yr−1) corrected for lensing magnification (μ = 3.00 ± 0.03), ~0.14 dex above the star-forming main sequence at z ~ 3. From the optimally extracted 1D grism spectrum (in particular the rest-frame optical nebular emission lines: [O III], Hβ, Hγ, and [O II]), we measure its global physical properties to be 12 + log(O/H)glob = 8.11+0.07−0.06, SFRN = 8.64+9.35−2.48 (M⊙ yr−1), and AV = 0.54+0.63−0.39, consistent with E(B − V)stars ~ E(B − V)gas.

Importantly, the new capabilities afforded by JWST/NIRISS (e.g., exquisite sensitivity, resolution, and wavelength coverage, etc.), coupled with gravitational lensing magnification, enable us to spatially resolve GLASS-Zgrad1 into >50 individual resolution elements with source-plane resolution reaching ~200 pc scales. Using its multiple nebular emission-line maps, we determine its metallicity radial gradient to be highly inverted (positive), i.e., Δ log(O/H)/Δr = 0.165 ± 0.023 [dex kpc−1]. This is the first-ever metallicity map from JWST spectroscopy, and the first sub-kpc resolution metallicity gradient ever measured at z ~ 3. We also verified this positive gradient slope through extensive tests. In particular, by removing the outermost spatial bin at r ~ 2 kpc showing significant metal enhancement, we rederived the gradient slope to be 0.076 ± 0.019 dex kpc−1, vindicating our finding that in `galname the abundance of metals increases with galacto-centric radius.

This strongly inverted metallicity gradient of GLASS-Zgrad1 likely stems from the close gravitational interaction with a nearby object—a dusty galaxy ~100× more massive than GLASS-Zgrad1 at a projected separation of ~15 kpc. This close encounter results in powerful tidal torques to induce metal-poor gas inflows to the inner regions of GLASS-Zgrad1, inverting its radial metallicity gradient. We thereby confirm a third channel for high-z galaxies showing a strongly inverted metallicity gradient, in addition to cold-mode accretion and metal-enriched gas outflows. Moreover, in light of the more pronounced inverted gradient measured in GLASS-Zgrad1 than any of the MAMMOTH-Grism gradient sources, we deduce that close gravitational interactions are more capable of producing strong environmental effects that modulate the chemical profiles of galaxies than large-scale overdensities (e.g., protocluster cores) at high redshifts. Our subsequent analysis of a larger sample within the GLASS-JWST data set will enable more comprehensive investigations of the true chemical profiles of galaxies at z ~ 3 so that we can make a quantitative comparison to simulations and hence cast more meaningful constraints on the effects of mergers, galactic feedback, and environments. This work marks the beginning of a new era for spatially resolved analysis of galaxy chemical evolution in and beyond the cosmic noon epoch.

We would like to thank the anonymous referee for careful reading and constructive comments that help improve the clarity of this paper. This work is based on observations made with the NASA/ESA/CSA James Webb Space Telescope. The data were obtained from the Mikulski Archive for Space Telescopes at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-03127 for JWST. These observations are associated with program JWST-ERS-1324. We acknowledge financial support from NASA through grant JWST-ERS-1324. X.W. is supported by CAS Project for Young Scientists in Basic Research, Grant No. YSBR-062. X.W. thanks Zach Hemler for kindly providing his compilations of gradient measurements from the literature and Patricia Tissera for providing the tabulated results of the latest EAGLE simulations. K.G. acknowledges support from Australian Research Council Laureate Fellowship FL180100060. M.B. acknowledges support from the Slovenian national research agency ARRS through grant N1-0238.

**ORCID iDs**

Xin Wang @ https://orcid.org/0000-0002-9373-3865
Tucker Jones @ https://orcid.org/0000-0001-5860-3419
Benedetta Vulcani @ https://orcid.org/0000-0003-0980-1499
Tommaso Treu @ https://orcid.org/0000-0002-8460-0390
Takahiro Morishita @ https://orcid.org/0000-0002-8512-1404
Guido Roberts-Borsani @ https://orcid.org/0000-0002-4140-1367
Matthew A. Malkan @ https://orcid.org/0000-0001-6919-1237
Alaina Henry @ https://orcid.org/0000-0002-6586-4446
Gabriel Brammer @ https://orcid.org/0000-0003-2680-005X
Victoria Strait @ https://orcid.org/0000-0002-6338-7295
Maruša Bradač @ https://orcid.org/0000-0001-5984-0395
Kristian Boyett @ https://orcid.org/0000-0003-4109-304X
Antonello Calabrò @ https://orcid.org/0000-0003-2536-1614
Marco Castellano @ https://orcid.org/0000-0001-9875-8263
Adriano Fontana @ https://orcid.org/0000-0003-3820-2823
Karl Glazebrook @ https://orcid.org/0000-0002-3254-9044
Patrick L. Kelly @ https://orcid.org/0000-0003-3142-997X
Nicha Leethochawalit @ https://orcid.org/0000-0003-4570-3159
Danilo Marchesini @ https://orcid.org/0000-0001-9002-3502
P. Santini @ https://orcid.org/0000-0002-9334-8705
M. Trenti @ https://orcid.org/0000-0001-9391-305X
Lilan Yang @ https://orcid.org/0000-0002-8434-880X

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