



First Peek with JWST/NIRCam Wide-field Slitless Spectroscopy: Serendipitous Discovery of a Strong [O III]/H α Emitter at $z = 6.11$

Fengwu Sun¹, Eiichi Egami¹, Nor Pirzkal², Marcia Rieke¹, Martha Boyer³, Matteo Correnti³, Mario Gennaro³, Julien Girard³, Thomas P. Greene⁴, Doug Kelly¹, Anton M. Koekemoer³, Jarron Leisenring¹, Karl Misselt¹, Nikolay Nikolov³, Thomas L. Roellig⁵, John Stansberry³, Christina C. Williams¹, and Christopher N. A. Willmer¹
(Members of the JWST/NIRCam Commissioning Team)

¹ Steward Observatory, University of Arizona, 933 N. Cherry Avenue, Tucson, AZ 85721, USA; fengwusun@arizona.edu

² ESA/AURA STScI, 3700 San Martin Drive, Baltimore, MD 21218, USA

³ Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

⁴ Space Science and Astrobiology Division, NASA Ames Research Center, MS 245-6, Moffett Field, CA 94035, USA

⁵ NASA Ames Research Center, MS 245-6, Moffett Field, CA 94035, USA

Received 2022 July 22; revised 2022 August 8; accepted 2022 August 12; published 2022 August 29

Abstract

We report the serendipitous discovery of an [O III] $\lambda\lambda 4959/5007$ and H α line emitter in the Epoch of Reionization (EoR) with the James Webb Space Telescope (JWST) commissioning data taken in the NIRCam wide-field slitless spectroscopy (WFSS) mode. Located $\sim 55''$ away from the flux calibrator P330-E, this galaxy exhibits bright [O III] $\lambda\lambda 4959/5007$ and H α lines detected at 3.7σ , 9.9σ , and 5.7σ , respectively, with a spectroscopic redshift of $z = 6.112 \pm 0.001$. The total H β + [O III] equivalent width is $664 \pm 98 \text{ \AA}$ ($454 \pm 78 \text{ \AA}$ from the [O III] $\lambda 5007$ line). This provides direct spectroscopic evidence for the presence of strong rest-frame optical lines (H β + [O III] and H α) in EoR galaxies as inferred previously from the analyses of the Spitzer/IRAC spectral energy distributions (SEDs). Two spatial and velocity components are identified in this source, possibly indicating that this system is undergoing a major merger, which might have triggered the ongoing starburst with strong nebular emission lines over a timescale of ~ 2 Myr, as our SED modeling suggests. The tentative detection of He II $\lambda 4686$ line (1.9σ), if real, may indicate the existence of very young and metal-poor star-forming regions with a hard UV radiation field. Finally, this discovery demonstrates the power and readiness of the JWST/NIRCam WFSS mode, and marks the beginning of a new era for extragalactic astronomy, in which EoR galaxies can be routinely discovered via blind slitless spectroscopy through the detection of rest-frame optical emission lines.

Unified Astronomy Thesaurus concepts: [Emission line galaxies \(459\)](#); [High-redshift galaxies \(734\)](#); [Starburst galaxies \(1570\)](#); [Galaxy spectroscopy \(2171\)](#); [Space telescopes \(1547\)](#); [James Webb Space Telescope \(2291\)](#)

1. Introduction

In the Epoch of Reionization (EoR; $z \gtrsim 6$), the rest-frame optical nebular emission lines (e.g., H α , H β , and [O III] $\lambda\lambda 4959/5007$) of galaxies were difficult to observe in the pre-James Webb Space Telescope (JWST) era. Typically being the brightest lines in the rest-frame optical bands, [O III] and H α get redshifted out of the near-infrared (NIR) K band at $z > 3.6$ and 2.5 , respectively, and therefore become inaccessible from the ground because of low sensitivity. At higher redshifts, these lines enter the passbands of the Spitzer/IRAC Channel 1/2 ($3.6/4.5 \mu\text{m}$), boosting broadband photometric measurements (e.g., Schaerer & de Barros 2009). Such an effect has been widely used to infer their line strengths at $z \simeq 3.8\text{--}5$ (H α ; e.g., Shim et al. 2011; Stark et al. 2013), $z \simeq 5.1\text{--}5.4$ (H α ; e.g., Rasappu et al. 2016), and $z \simeq 6.7\text{--}7.0$ (H β and [O III]; e.g., Smit et al. 2014, 2015; Endsley et al. 2021a, 2021b). Possible modulation of observed IRAC [$3.6 \mu\text{m}$]–[$4.5 \mu\text{m}$] colors by emission lines was also reported for galaxies even at $z \sim 8$ (e.g., Labbé et al. 2013; De Barros et al. 2019). Despite all of this exciting evidence, up to now, all of these optical emission-line studies in the EoR relied on broadband

photometry, which is inevitably affected by multiple factors such as the assumptions of star formation history, metallicity, ionization parameter, and dust attenuation.

The JWST will undoubtedly revolutionize the studies of rest-frame optical-line emitters at high redshift (see a recent review by Robertson 2022). With its unprecedented sensitivity, JWST will detect H α emission up to $z \sim 6.7$ and [O III] emission up to $z \sim 9$ with two of the four scientific instruments, NIRCam and NIRSpec. The wide-field slitless spectroscopy mode of NIRCam (Greene et al. 2017) conducts grism spectroscopy at $2.4\text{--}5.0 \mu\text{m}$ with a medium spectral resolution of $R \sim 1600$ around $4 \mu\text{m}$. With a dispersion of around 1 nm pixel^{-1} , one cannot obtain the full $2.4\text{--}5 \mu\text{m}$ spectrum simultaneously across the detector, which has 2040 pixels in each dimension. Therefore, a filter is also needed to ensure that desired wavelengths are captured on the detector. A filter will also minimize IR background and its associated noise from the telescope and sky. Combining the data taken with the two long-wavelength modules of NIRCam, an instantaneous survey area of up to $\sim 9 \text{ arcmin}^2$ can be reached (in which sources yield either partial or complete spectra), enabling efficient wide-field surveys of line-emitting galaxies in the EoR. Multiple JWST Cycle-1 Early Release Science (ERS) and General Observers (GO) programs (e.g., CEERS, PI: Finkelstein; ASPIRE, PI: Wang; FRESCO, PI: Oesch) will exploit this powerful observing mode by detecting $> 10^2 \sim 10^3$ [O III] and H α line emitters at $z \gtrsim 6$.



Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](#). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

In this work, we present the first serendipitous spectroscopic discovery of an [O III] $\lambda\lambda 4959/5007$ and H α line emitter at $z > 6$ with the JWST/NIRCam WFSS mode. The galaxy, named NRCJ1631+3008-z6.1, was discovered in the field around the flux calibrator P330-E (GSC 02581-02323), which was observed during the commissioning phase of this observing mode. The detection of [O III] $\lambda\lambda 4959/5007$ and H α emission lines at 3.528, 3.562, and 4.668 μm indicates a spectroscopic redshift of $z = 6.112 \pm 0.001$. The observations and corresponding data reduction techniques are described in Section 2. The spectroscopic, photometric measurements, and spectral energy distribution (SED) modeling are presented in Section 3. In Section 4, we compare our results with pre-JWST-era studies at $z \simeq 0-7$ and discuss the implication of emission-line strengths. The conclusions can be found in Section 5. Throughout this Letter, we assume a flat Λ CDM cosmology with $h = 0.7$ and $\Omega_m = 0.3$, and a Chabrier (2003) initial mass function (IMF). The AB magnitude system (Oke & Gunn 1983) is used.

2. Observation and Data Reduction

The JWST/NIRCam long-wavelength (LW; 2.4–5.0 μm) grism characterization observations were obtained through Program #1076 (PI: Pirzkal) during the commissioning phase of the instrument. NIRCam has four grisms: each of the two modules (A and B) has two grisms that disperse light parallel to detector rows (Grism R) or columns (Grism C), respectively. For the flux and wavelength calibration, P330-E (a G2V star) and IRAS 05248-7007 (a post-asymptotic-giant-branch star in the Large Magellanic Cloud) were observed, respectively.

The WFSS observations of the P330-E field were obtained with both F322W2 and F444W filters on 2022 April 29. In each band, the target was observed with four grisms (AR, AC, BR, and BC) at four INTRAMODULEX primary dither positions, respectively. With a five-group BRIGHT1 readout pattern, the effective time per integration was 96 s. This resulted in a signal-to-noise ratio (S/N) of $\gtrsim 100$ (per pixel, ~ 1 nm) for the extracted 1D spectrum of P330-E in each exposure, enabling accurate flux calibration over the full wavelength range of NIRCam WFSS mode. We note that the last exposure with the Module B Grism C in the F322W2 band (Observation #108, Visit 001, and Exposure 4) failed because of unstable guiding, and therefore these data were not included in the analysis. The effective total exposure time of each source depends on its location, with a maximum of ~ 25 minutes in each band after combining exposures with all grisms.

The WFSS data were reduced to the level of Stage-1 (i.e., “_RATE” files) with the standard JWST calibration pipeline⁶ v1.4.7. After that, we performed the 2D sky-background subtraction using the sigma-clipped median images, which were constructed from the obtained WFSS data. We then applied flat-field correction using the imaging flat data obtained with the same filter and module. The world coordinate system (WCS) of each grism image was calibrated with the GAIA DR2 catalog (Gaia Collaboration et al. 2018) by matching with the stars detected in the NIRCam short-wavelength (SW) images, which were taken simultaneously in the F212N band.

The imaging data of the P330-E field were taken either simultaneously with the grism exposures (F212N) or after the grism observations through direct and out-of-field imaging

(SW: F212N; LW: F250M, F322W2, and F444W). The direct-imaging data were reduced and mosaicked using the standard Stage-1/2/3 JWST pipeline. We also manually adjusted the photometric zero-points of these image products based on the in-flight measurements of P330-E (see Rigby et al. 2022) by -0.11 , 0.06 , 0.15 , and 0.21 mag with the F212N, F250M, F322W2, and F444W bands, respectively, as the revised photometric zero-points were not incorporated in the early pipeline version that we used. The revised zero-points are consistent with those in the latest reference files “jwst_0942.pmap” at the time of writing. The final image products were resampled to a native pixel size of $0''.0312$ (SW) and $0''.0629$ (LW) with `pixfrac` = 0.8, and the WCSs of the images were registered with the Gaia DR2 catalog (Gaia Collaboration et al. 2018). The effective exposure times (t_{exp}) at the location of our source, NRCJ1631+3008-z6.1, are 33.8, 6.4, 2.5, and 3.2 minutes in the F212N, F250M, F322W2, and F444W bands, respectively.

We also note that although P330-E was frequently observed as a flux calibrator for the Hubble Space Telescope (HST) and JWST, most of the existing data are too shallow and our source was not detected. Ground-based $g/r/z$ -band images (e.g., the Mosaic z -band Legacy Survey and the Beijing-Arizona Sky Survey; Dey et al. 2019; Zou et al. 2019) were also checked, but the data were too shallow to constrain the SED (3σ upper limits at $g > 24.8$ and $z > 23.6$ mag) of NRCJ1631+3008-z6.1.

We performed source extraction with the mosaicked F322W2 and F444W images using SExtractor v2.25.3 (Bertin & Arnouts 1996). With the derived source catalog, we conducted 2D spectral extraction, wavelength, and flux calibration on the flat-fielded WFSS data, and combined the extracted data taken with Grism R, C, or both. These were performed for ~ 3000 sources detected in the F322W2 image, to test the accuracy of derived spectral tracing and dispersion models in the instrument commissioning phase. We defer the detailed descriptions of these models to another paper from the collaboration. Qualitatively, for a given source with direct-imaging position of (x_0, y_0) in an exposure, our dispersion model can predict the position of a spectral feature at a wavelength of λ_s along the dispersion direction (e.g., x_s in Grism R) with an rms accuracy of 0.2 pixel, i.e., $\sim 10\%$ of the resolution element. With the derived x_s , our spectral tracing model can predict the position along the perpendicular direction (e.g., y_s in Grism R) with an rms accuracy of 0.1–0.2 pixel, i.e., 5%–10% of the FWHM of the point-source spectral trace.

3. Results

3.1. Discovery of an [O III] $\lambda 5007$ Emitter at $z = 6.112$

Through visual inspection of extracted spectra, we identified a source with a prominent emission-line feature at 3.562 μm (NRCJ1631+3008-z6.1; Figure 1). Located $\sim 55''$ away from P330-E, this source was observed with Grism R in five integrations of exposure ($t_{\text{exp}} = 8$ minutes) and Grism C in seven integrations ($t_{\text{exp}} = 11$ minutes). We note that this source could potentially yield spectra in two additional integrations with the Module A Grism R (Observation #106, Visit 001, and Exposure 2/3), but the direct-imaging position of the source was near the edge of the pick-off mirror. We did not include these data as the emission line was not seen in these integrations, suggesting a significant loss of the target signal. The 2D spectra of this source overlapped with two continuum

⁶ <https://github.com/spacetelescope/jwst>

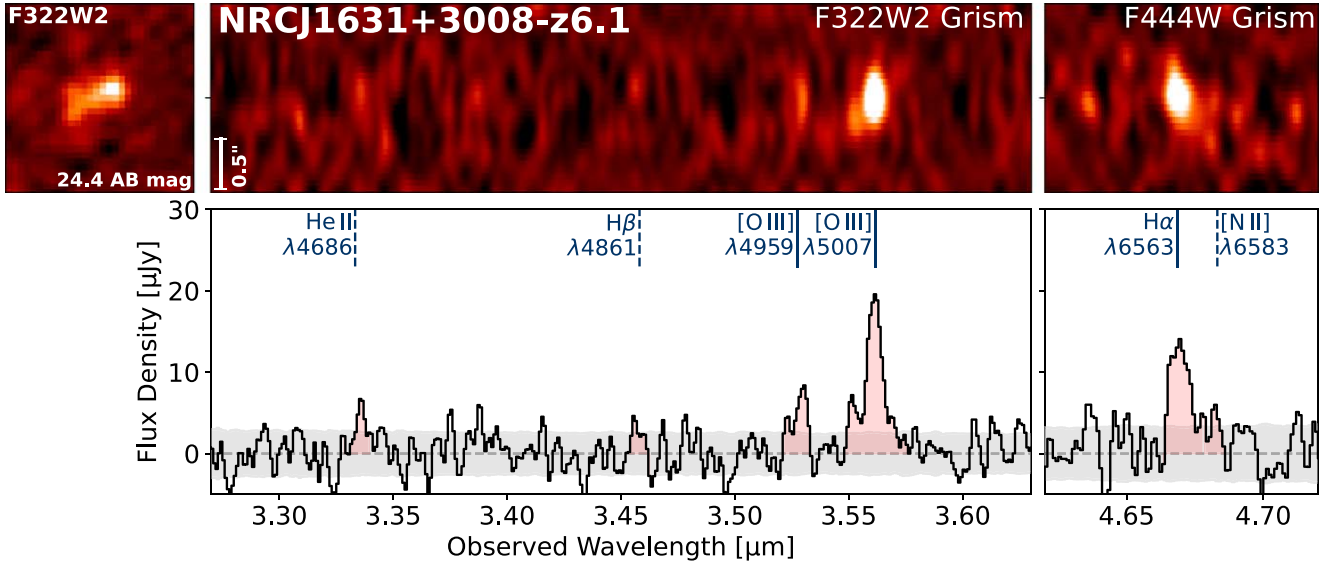


Figure 1. JWST/NIRCam F322W2 image (top-left; size: $1''.9 \times 1''.9$), 2D, and 1D spectra (top/bottom-middle/right) of NRCJ1631+3008-z6.1 in the F322W2 and F444W band. Image and 1D spectra were smoothed with a Gaussian kernel of $\sigma = 1$ pix ($0''.063$ or 1 nm) and 2D spectra were smoothed with $\sigma = 2$ pix. All spectra were flux-calibrated and background-subtracted. 1D spectra were extracted within $D = 7$ pix ($0''.44$) box with aperture correction factors applied (modeled from the profiles of the [O III] $\lambda 5007$ and $H\alpha$ line). Six identified lines (He II $\lambda 4686$, $H\beta$, [O III] $\lambda\lambda 4959/5007$, $H\alpha$, and [N II] $\lambda 6583$) at $z = 6.112 \pm 0.001$ are labeled with dark blue lines and highlighted with shallow red shades. 1D error spectra are shown as the gray-shaded regions.

sources around $3.5 \mu\text{m}$ in the Module B Grism R (four integrations). In the combined 2D spectra, we subtracted 1D continuum and background along both the row and column direction through linear fitting in the line/source-free region. This reduced the rms noise by $\sim 20\%$ and the resultant background can be well described with a normal distribution with zero mean through the Kolmogorov–Smirnov test (p -value = 0.43). 1D spectra were extracted using a box aperture with the height $D = 7$ pix ($0''.44$), which optimized the S/N of the second brightest emission line at $3.528 \mu\text{m}$. An aperture correction factor was calculated as 1.07, using the $3.562 \mu\text{m}$ line profile in the vertical direction.

The two lines detected at $3.562 \mu\text{m}$ (9.9σ) and $3.528 \mu\text{m}$ (3.7σ) were identified as [O III] $\lambda\lambda 5007/4959$ emissions at $z = 6.112 \pm 0.001$. We also searched for other possible emission lines in extracted spectra, and tentatively identified He II $\lambda 4686$ (1.9σ) and $H\beta$ $\lambda 4861$ (1.5σ) lines. [O II] $\lambda\lambda 3726/3729$ doublet lines were not detected in the F322W2 spectrum ($< 4 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$) because of a twice higher rms noise at the expected wavelength. We also identified $H\alpha$ (5.7σ) and [N II] $\lambda 6583$ (1.4σ) in the F444W spectra at the expected wavelengths (right panels of Figure 1). We modeled the profiles of four identified lines in the F322W2 band with the Gaussian functions simultaneously, and in this fitting, the FWHM and flux of each line were allowed to float, while the line centers were controlled by the redshift parameter. The best-fit spectroscopic properties are presented in Table 1. Measurements using Grism R-only or C-only 1D spectra returned consistent line fluxes. We observed a flux ratio of 2.9 ± 0.8 between the identified [O III] $\lambda\lambda 5007/4959$ lines, consistent with the theoretical ratio of three. $H\alpha$ and [N II] lines were modeled with similar methods, and the detailed analysis of these lines will be presented in another paper from the collaboration with a larger sample of $z \gtrsim 6$ $H\alpha$ emitters.

3.2. Two Spatial and Velocity Components

Figure 2 displays the 2D spectra of NRCJ1631+3008-z6.1 obtained with the orthogonal Grism R and C separately. [O III]

Table 1
Summary of the Properties of NRCJ1631+3008-z6.1

Photometric Properties	
R.A.	16:31:34.45
Decl.	+30:08:10.6
F212N [AB mag]	>23.8
F250M [AB mag]	>24.8
F322W2 [AB mag]	24.45 ± 0.09
F444W [AB mag]	24.53 ± 0.17
Spectroscopic Properties	
Redshift	6.112 ± 0.001
$f(\text{He II } \lambda 4686)$ [$10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$]	9.9 ± 5.2
$f(H\beta)$ [$10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$]	5.0 ± 3.2
$f([\text{O III}] \lambda 4959)$ [$10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$]	14.2 ± 3.9
$f([\text{O III}] \lambda 5007)$ [$10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$]	40.5 ± 4.1
$f(H\alpha)$ [$10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$]	16.0 ± 2.8
$f([\text{N II}] \lambda 6583)$ [$10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$]	3.3 ± 2.3
EW(He II $\lambda 4686$) [\AA]	97 ± 52
EW($H\beta$) [\AA]	52 ± 35
EW([O III] $\lambda 4959$) [\AA]	156 ± 47
EW([O III] $\lambda 5007$) [\AA]	454 ± 78
EW($H\alpha$) [\AA]	369 ± 104
EW([N II] $\lambda 6583$) [\AA]	76 ± 56
EW($H\beta$ + [O III]) [\AA]	664 ± 98
FWHM([O III] $\lambda 5007$) [km s^{-1}]	382 ± 130
FWHM($H\alpha$) [km s^{-1}]	267 ± 109
Physical Properties	
R_c [kpc]	1.2 ± 0.1
SFR($H\alpha$) [$M_\odot \text{ yr}^{-1}$]	36 ± 6
SFR(UV, SED) [$M_\odot \text{ yr}^{-1}$]	23 ± 6
M_{star} [$10^8 M_\odot$]	10 ± 8
$\log[\xi_{\text{ion}}/(\text{erg}^{-1}\text{Hz})]$	25.3 ± 0.1

Note. The uncertainty of absolute flux calibration is estimated as between 2% (according to Gordon et al. 2022) and 5% (conservative), considerably smaller than the observational errors presented in this table. The derivation of EWs is detailed in Section 3.3.

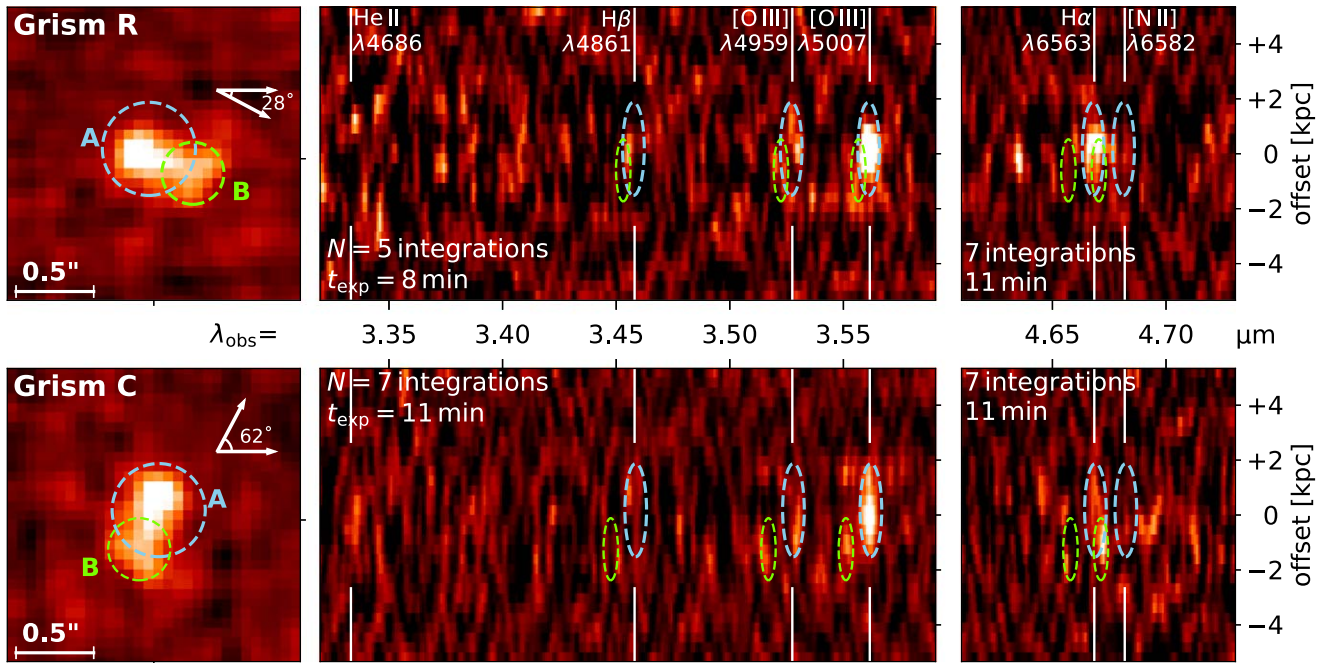


Figure 2. JWST/NIRCam F322W2 direct image and F322W2/F444W 2D spectra of NRCJ1631+3008-z6.1 seen with Grism R (top) and C (bottom). The orientations of direct images have been aligned to the dispersion directions of the two grisms. In the plots of 2D spectra, the expected positions of detectable emission lines are indicated with vertical white lines. [O III] $\lambda\lambda 4959/5007$ and $H\alpha$ lines can be detected with Grism R and C data separately, confirming the line identification. Two potential clumpy structures (A and B) with a spatial offset of 1.6 ± 0.3 kpc and a velocity offset of 602 ± 105 km s $^{-1}$ are noted with dashed blue and green circles in direct images, respectively, and the expected locations of corresponding line emissions ([O III], $H\alpha$, and [N II]) are shown with dashed circles of the same colors superimposed on the 2D spectra. The PAs of the two clumps with respect to the dispersion directions are also shown in the direct images.

and $H\alpha$ lines can be detected in the two spectra individually, further confirming the line identification and association with the source.

From the F322W2 image, we identified two spatial components labeled as clump-A and B with a physical separation of 1.6 ± 0.3 kpc between their centroids. The dispersion direction of Grism C was off by $62^\circ \pm 7^\circ$ from the position angle (PA) of the two clumps, and two clumps of [O III] $\lambda 5007$ emissions can be identified on the 2D spectrum with Grism C. Similar clumps can also be tentatively seen for [O III] $\lambda 4959$, albeit at much lower significance. These can also be seen as the major and minor peaks of [O III] lines in the 1D spectrum (Figure 1). Through both 1D line profile fitting and aperture photometry of the [O III] $\lambda 5007$ emission lines in the spectra, we measured a flux ratio of 2.6 ± 0.6 between the two [O III] clumps.

The offset between the two clumps in spectral image is a result of both intrinsic velocity offset and projected physical offset along the dispersion direction, and the velocity offset was measured as 605 ± 102 km s $^{-1}$. In the Grism R data, the dispersion direction was only off by $28^\circ \pm 7^\circ$ from the PA between clump-A/B, leading to a strong spectral overlapping between the two clumps. As a result, the overall line width seen with Grism R, which was convolved with the surface brightness profile of the source in dispersion direction, is also larger than that measured from the Grism C data. The deconvolved (intrinsic) FWHM of [O III] $\lambda 5007$ line is measured as 362 ± 134 km s $^{-1}$ from both the Grism R and C data.

We also examined such a two-component model with the F444W spectra. Interestingly, we found that the bulk of the $H\alpha$ emission is from clump-A, which can also be tentatively seen for $H\beta$ emission with F322W2 data despite a lower

significance. In contrast, clump-B hosts more luminous [N II] emission that overlaps with the $H\alpha$ emissions from clump-A in the wavelength space with both grisms. The [N II] emissions from clump-B can be clearly seen in Grism C data where the perpendicular offset of the two clumps is larger. A higher [N II]/ $H\alpha$ ratio in clump-B (>1.2) compared with clump-A (0.25 ± 0.17) may indicate elevated metallicity and/or harder UV radiation field in clump-B.

3.3. Photometry and SED Modeling

We performed aperture photometry of NRCJ1631+3008-z6.1 (both clumps together) in F212N, F250M, F322W2, and F444W images with a circular aperture of $r = 0''.45$ using PHOTUTILS (Bradley et al. 2022). The circularized surface brightness profile modeled in the F322W2 band (effective radius $R_e = 0''.22 \pm 0''.02$; 1.2 ± 0.1 kpc after deconvolving the point-spread function) suggests that the aperture correction is negligible. The sky background was subtracted using the median of sigma-clipped local annulus, and the photometric uncertainty was computed using the rms of that. The source was detected in the wide F322W2 (24.45 ± 0.09 mag) and F444W (24.53 ± 0.17 mag) bands, but remained undetected in either the F212N or F250M band (3σ upper limits of >23.8 and >24.8 mag, respectively; Figure 3). The nondetection in the F212N/F250M band can be explained by their smaller bandwidths in contrast to those of wide filters, and lack of luminous line emission within their wavelength ranges.

We then conducted SED modeling with CIGALE (Boquien et al. 2019). In addition to the four-band photometry, the equivalent widths (EWs) of $H\beta$, [O III], and $H\alpha$ lines were also included as constraints. These line EWs were calculated using the measured line fluxes and the underlying F322W2/F444W

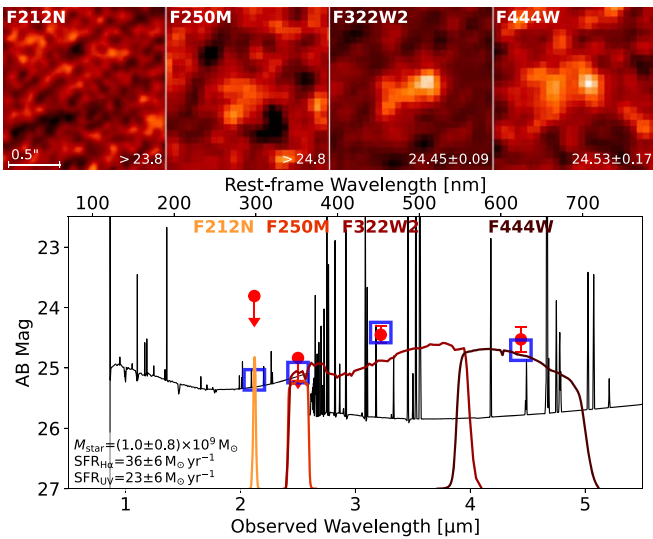


Figure 3. Top: JWST/NIRCam short-wavelength (F212N) and long-wavelength (F250M, F322W2, and F444W) cutout images of NRCJ1631-3008-z6.1. Measured source brightness in each filter is shown in the lower-right corner of each plot (in AB mag; 3σ upper limit for non-detection). Bottom: best-fit SED model obtained with CIGALE (black curve; Boquien et al. 2019). Photometric measurements are shown as red circles, and best-fit source brightnesses are shown as open blue squares. The transmission curves of four utilized filters are also plotted for comparison. Note that the transmission of the F322W2 band is computed using the measured grism throughput and is different from that in the JWST User Documentation.

continuum flux densities, which were computed from broadband photometry by subtracting all measured line fluxes within the passband and were assumed as constant across the bandwidth. All line EWs are reported in Table 1. We assumed a commonly used delayed star formation history (SFH; `sfhdelayed`) with an optional late starburst, and allowed a metallicity range of $0.2 Z_{\odot} - Z_{\odot}$. The allowed range of ionization parameter ($\log U$) was set as $-1 \sim -2$ given the presence of strong [O III] and He II lines, and a modified Calzetti et al. (2000) attenuation curve was adopted.

The best-fit SED model is shown in the lower panel of Figure 3. The best-fit SFH model invokes both young (1–2 Myr) and old (~ 500 Myr) stellar populations to interpret both strong optical emission lines and underlying stellar continuum. Similar models have been reported for $z > 6$ galaxies with the presence or evidence of strong nebular lines (e.g., Hashimoto et al. 2018; Jiang et al. 2020; Whitler et al. 2022). The reduced χ^2 of best-fit line EWs is 0.65. The dust attenuation is negligible, and the best-fit metallicity is $\sim 0.4 Z_{\odot}$. We derived a stellar mass of $(1.0 \pm 0.8) \times 10^9 M_{\odot}$. In order to compare our star formation rate (SFR) measurement with rest-frame-UV-selected galaxies at $z > 6$, we derived a UV SFR of $23 \pm 6 M_{\odot} \text{ yr}^{-1}$ from the best-fit SED. Although the UV continuum of NRCJ1631+3008-z6.1 was not directly detected in any band, the inferred SFR (UV, SED) is comparable with the SFR derived with $\text{H}\alpha$ luminosity ($36 \pm 6 M_{\odot} \text{ yr}^{-1}$), assuming the $\text{H}\alpha$ luminosity–SFR conversion in Kennicutt & Evans (2012).

4. Discussion

4.1. Comparisons with Galaxies across $z \simeq 0-7$

We compare the emission-line and physical properties of NRCJ1631+3008-z6.1 with those of galaxies across $z \simeq 0-7$ in Figure 4.

In the left panel, we first compare the measured $\text{H}\beta + [\text{O III}]$ EW with $z \sim 6.8$ galaxies in Endsley et al. (2021a, 2021b). In the pre-JWST era, $\text{H}\beta + [\text{O III}]$ EWs at $z \gtrsim 4$ can only be inferred through the modeling of Spitzer/IRAC SEDs within certain redshift windows (e.g., $z \simeq 6.7 - 7.0$). Endsley et al. (2021b) reported a median $\text{H}\beta + [\text{O III}]$ EW of 759^{+112}_{-113} Å for UV-luminous ($M_{\text{UV}} \lesssim -21$, $\text{SFR}_{\text{UV}} \gtrsim 10 M_{\odot} \text{ yr}^{-1}$) galaxies at $z \simeq 6.8$. With the data presented here, we show that the $\text{H}\beta + [\text{O III}]$ EW of NRCJ1631+3008-z6.1 (664 ± 98 Å) is consistent with those of $z \sim 6.8$ galaxies with comparable stellar mass and SFR_{UV} . This confirms the presence of prominent rest-frame optical nebular emission lines in EoR galaxies, which are more than an order-of-magnitude stronger than those of galaxies in the local universe with comparable stellar masses (e.g., Sloan Digital Sky Survey (SDSS)-selected galaxies; Maraston et al. 2013; Thomas et al. 2013).

In the middle panel, we compare the $\text{H}\alpha$ and [O III] $\lambda 5007$ EWs of NRCJ1631+3008-z6.1 with extreme emission-line galaxies at $z = 1.3-2.4$ (Tang et al. 2019), where these redshifted optical emission lines are still accessible for ground-based NIR spectroscopy. The $\text{H}\alpha$ EW of our source is consistent with those of $z = 1.3-2.4$ galaxies with similar [O III] EWs. We also compute the hydrogen-ionizing photon production efficiency (ξ_{ion}) using the observed $\text{H}\alpha$ (tracing ionizing photons) and inferred UV luminosity following the same procedure in Shivaei et al. (2018) and Tang et al. (2019). We derive a $\log[\xi_{\text{ion}}/(\text{erg}^{-1}\text{Hz})] = 25.3 \pm 0.1$ for NRCJ1631+3008-z6.1, which is widely seen in emission-line galaxies at $z \sim 2$ (e.g., Shivaei et al. 2018). The derived ξ_{ion} is also consistent with those of the $z \sim 2$ galaxies on the $\xi_{\text{ion}} - \text{EW}(\text{O III})$ relation modeled by Tang et al. (2019). This suggests that the physical properties of certain strong line-emitting galaxies at $z \sim 2$ and $z > 6$ may be similar.

One potential surprising discovery of this work is the tentative detection of the He II $\lambda 4686$ line. We examine the strength of the He II line in all 12 available integrations. The line flux remains positive in nine integrations (75%), consistent with the expectation (72%) from Gaussian statistics for a 2σ stacked signal. The production of helium recombination lines require sufficient ionizing photons with energy greater than 54.4 eV, much higher than the requirements for hydrogen (13.6 eV) and [O III] (35.1 eV) lines, and a very low-metallicity environment ($\lesssim 0.01 Z_{\odot}$) is required to interpret a large He II EW ($\gtrsim 100$ Å; e.g., Inoue 2011). In the right panel of Figure 4, we show the $\text{EW}(\text{He II } \lambda 4684)$ versus $\text{EW}([\text{O III}] \lambda 5007)$ of NRCJ1631+3008-z6.1 compared to those of extreme emission-line galaxies (Senchyna et al. 2017, 2020, mostly powered by X-ray binaries) and SDSS active galactic nuclei (AGNs; Oh et al. 2011; Bär et al. 2017) in the local universe, which were detected in He II $\lambda 4686$. At a given [O III] EW, the He II EW of NRCJ1631+3008 is higher than those of all comparison samples at $z \sim 0$.

We note that a well-known Ly α -emitting galaxy, CR7 at $z = 6.6$, was reported for a possible detection of He II $\lambda 1640$ lines with ground-based and HST grism spectroscopy (Sobral et al. 2015, 2019; but see also Shibuya et al. 2018 claiming no detection of this line). The He II $\lambda 4686$ line is 60% more luminous than the He II $\lambda 1640$ line in Case B recombination with an electron temperature of $T_e = 10^4$ K (Osterbrock & Ferland 2006). The tentative detection of the He II $\lambda 4686$ line may indicate an elevation of the hardness of the ionizing spectrum in certain EoR galaxies, i.e., a larger fraction of

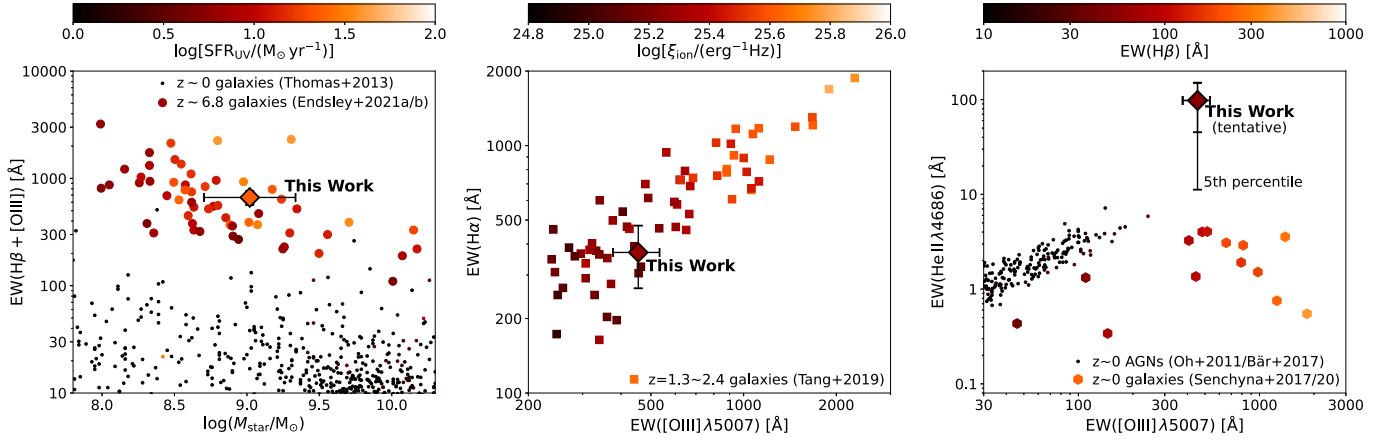


Figure 4. Comparisons of emission-line equivalent widths of NRCJ1631+3008-z6.1 (colored diamonds with black edges) with those of galaxies across $z \simeq 0-7$. Left: $H\beta + [O\text{ III}]$ line EW vs. the stellar mass of NRCJ1631+3008-z6.1 compared with those of $z \sim 6.8$ galaxies whose EWs are inferred from Spitzer/IRAC $[3.6\ \mu\text{m}]$ – $[4.5\ \mu\text{m}]$ color (circles; Endsley et al. 2021a, 2021b), and also SDSS-selected galaxies in the local universe (dots; Thomas et al. 2013). Sources at $z > 6$ are color-coded by their UV-based SFRs. Middle: $H\alpha$ EW vs. $[O\text{ III}] \lambda 5007$ EW compared with those of extreme emission-line galaxies at $z = 1.3-2.4$ (squares; Tang et al. 2019). Sources are color-coded by their ionizing photon production efficiency (ξ_{ion}). Right: He II $\lambda 4686$ EW vs. $[O\text{ III}] \lambda 5007$ EW compared with those of extreme emission-line galaxies (hexagons; Senchyna et al. 2017, 2020) and SDSS-selected He II AGNs (dots; Oh et al. 2011; Bär et al. 2017) in the local universe. Sources are color-coded with their $H\beta$ EWs. Given the low significance of He II $\lambda 4686$ detection with NRCJ1631+3008-z6.1, we show the 5th, 16th, and 84th percentiles of the likelihood distribution of the He II EW.

ionizing photons with high energy (>54.4 eV) when compared with those seen at ionizing environments at lower redshifts (He II EW $\lesssim 10$ Å even in so-called Wolf-Rayet galaxies; e.g., Brinchmann et al. 2008; Cassata et al. 2013). This may further indicate a young (1–2 Myr) metal-poor (i.e., “Pop III”-like) stellar population produced with a top-heavy IMF (e.g., Jeřábková et al. 2017) with the existence of very massive stars over $300 M_{\odot}$ (e.g., Schaerer 2002, which could produce He II EW at $\gtrsim 100$ Å) and/or a higher binary fraction. However, we also make the caveat clear that the significance of He II detection is low (1.9σ) with the shallow commissioning data and no decisive conclusion could be made. Deeper He II $\lambda 1640$ or $\lambda 4684$ spectroscopy is necessary to disentangle the physics behind this puzzling tentative detection.

4.2. Overall Physical Picture of NRCJ1631+3008-z6.1

The two spatial and velocity components of NRCJ1631+3008-z6.1 resolved with JWST/NIRCam imaging and slitless spectroscopy suggest that this source is a galaxy pair. Assuming a constant mass-to-light ratio for the two components, the mass ratio is 2.6 ± 0.6 , satisfying the classification criterion of a major merger event. The dynamic timescale computed from the spatial and velocity offset of the two components is 2–3 Myr, consistent with the timescale of the late starburst (1–2 Myr) indicated by the strong nebular lines as modeled in Section 3.3. Therefore, it is possible that the strong optical emission lines and ongoing star formation seen in this source is triggered by the merger of the two galaxies undergoing the final coalescence phase.

The two components are unlikely two star-forming clumps in the same galaxy, because the corresponding dynamic mass $M_{\text{dyn}} = v^2 R / G \sim 10^{11} M_{\odot}$ would be much larger than one typically expects for a galaxy with a stellar mass of $10^9 M_{\odot}$. In addition to this, the physical extent of NRCJ1631+3008-z6.1 is also twice larger than those of galaxies with comparable UV luminosity and stellar mass at $z \sim 6$ (e.g., Shibuya et al. 2015), making the system more likely a merger pair.

Although the $[O\text{ III}]$, $H\beta$, and $H\alpha$ line properties of NRCJ1631+3008-z6.1 are consistent with those of emission-line galaxies at intermediate ($z \sim 2$) and high redshifts ($z \sim 6.8$), the tentative He II detection is not expected based on the majority of existing literature except for a few rare cases (e.g., CR7; Sobral et al. 2019). We note that both CR7 and NRCJ1631+3008-z6.1 show clear morphological and kinematic evidence of a merger (Sobral et al. 2015; Matthee et al. 2017), and it is possible that He II can originate from certain merging young and gaseous clumps with very low metallicity, which are barely enriched before the coalescence. The spatial distribution of metallicity in such systems can be uneven as shown in the 2D spectra of the $[N\text{ II}]$ line. Given the shallowness of obtained data, deeper integral field unit observations (e.g., with JWST/NIRSpec) will be highly valuable to shed light on the potential existence of low-metallicity star-forming clumps in galaxies at the so-called “Cosmic Dawn” ($z \gtrsim 6$).

5. Conclusion

We report the serendipitous discovery of an $[O\text{ III}] \lambda\lambda 4959/5007$ and an $H\alpha$ line-emitting galaxy in the Epoch of Reionization with JWST/NIRCam wide-field slitless spectroscopy. The galaxy, NRCJ1631+3008-z6.1, is located $\sim 55''$ apart from the flux calibrator P330-E, and was observed with JWST/NIRCam in the F322W2 and F444W bands using both the imaging and slitless spectroscopy modes during the commissioning phase. $[O\text{ III}] \lambda\lambda 4959/5007$ and $H\alpha$ lines were detected in both the Grism R and C data separately, confirming the line identification with a spectroscopic redshift of $z = 6.112 \pm 0.001$. The He II $\lambda 4686$, $H\beta$, and $[N\text{ II}] \lambda 6583$ lines are also detected tentatively.

The equivalent widths of the $[O\text{ III}]$, $H\beta$, and $H\alpha$ lines are consistent with those of emission-line galaxies at $z \simeq 1-2$, which are measured through ground-based near-IR spectroscopy, and also those of galaxies at $z \sim 6.8$, which are inferred from Spitzer/IRAC $[3.6\ \mu\text{m}]$ – $[4.5\ \mu\text{m}]$ colors. This provides direct spectroscopic evidence for the presence of strong rest-

frame optical nebular emission lines in galaxies at $z > 6$. The tentative detection of He II $\lambda 4686$, however, is inconsistent with those observed in either extreme emission-line galaxies or AGNs in the local universe. If real, this may indicate the existence of very young and metal-poor star-forming regions with a hard UV radiation field in NRCJ1631+3008-z6.1.

We show that NRCJ1631+3008-z6.1 consists of two spatial and velocity components (clump-A/B) that are undergoing the final coalescence stage of a major merger. The dynamic timescale (2–3 Myr) of the merger is consistent with the timescale of the late starburst (1–2 Myr) modeled through SED fitting, indicating that the merger triggers the recent starburst and strong optical nebular emission lines ([O III] and $H\alpha$). Clump-B shows higher [N II]/ $H\alpha$ ratio than clump-A, which may indicate a higher metallicity. Under-enriched gaseous clumps can be the source of potential He II emission seen in $z > 6$ merging galaxies, which could be tested with deep near-IR integral field spectroscopy in the JWST era.

Finally, the serendipitous discovery of NRCJ1631+3008-z6.1 in the commissioning phase demonstrates the scientific readiness and excellent capability of the JWST/NIRCam WFSS mode. It also marks the beginning of the JWST era for extragalactic astronomy, in which galaxies at $z \gtrsim 6$ can be routinely discovered and confirmed through wide-field slitless spectroscopy (see also the detections of [O III] $\lambda\lambda 4363/4959/5007$ lines for $z > 6$ galaxies with JWST/NIRSpec early release observations; Pontoppidan et al. 2022).











We thank Mengtao Tang for sharing his measurements of emission-line galaxies at $z = 1.3$ – 2.4 . We thank the anonymous referee for a helpful and prompt report. We thank Pavel Kroupa and Daniel Stark for helpful comments. F.S., E.E., M.R., D.K., J.L., K.M., C.C.W., and C.N.A.W. acknowledge funding from JWST/NIRCam contract to the University of Arizona, NAS5-02105. 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 #1076. This paper is based upon High Performance Computing (HPC) resources supported by the University of Arizona TRIF, UITS, and Research, Innovation, and Impact (RII) and maintained by the UArizona Research Technologies department. All of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST) at the Space Telescope Science Institute. The specific observations analyzed can be accessed via <https://doi.org/10.17909/f8p1-e696>.

Facilities: JWST (NIRCam).

Software: ASTROPY (Astropy Collaboration et al. 2013, 2018), SEXTRACTOR (Bertin & Arnouts 1996), PHOTUTILS (Bradley et al. 2022), CIGALE (Boquien et al. 2019).

ORCID iDs

Fengwu Sun  <https://orcid.org/0000-0002-4622-6617>
 Eiichi Egami  <https://orcid.org/0000-0003-1344-9475>
 Nor Pirzkal  <https://orcid.org/0000-0003-3382-5941>
 Marcia Rieke  <https://orcid.org/0000-0002-7893-6170>
 Martha Boyer  <https://orcid.org/0000-0003-4850-9589>
 Matteo Correnti  <https://orcid.org/0000-0001-6464-3257>

Mario Gennaro  <https://orcid.org/0000-0002-5581-2896>
 Julien Girard  <https://orcid.org/0000-0001-8627-0404>
 Thomas P. Greene  <https://orcid.org/0000-0002-8963-8056>
 Anton M. Koekemoer  <https://orcid.org/0000-0002-6610-2048>
 Jarron Leisenring  <https://orcid.org/0000-0002-0834-6140>
 Nikolay Nikolov  <https://orcid.org/0000-0002-6500-3574>
 Thomas L. Roellig  <https://orcid.org/0000-0002-6730-5410>
 John Stansberry  <https://orcid.org/0000-0003-2434-5225>
 Christina C. Williams  <https://orcid.org/0000-0003-2919-7495>
 Christopher N. A. Willmer  <https://orcid.org/0000-0001-9262-9997>

References

- Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., et al. 2018, *AJ*, 156, 123
- Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, *A&A*, 558, A33
- Bär, R. E., Weigel, A. K., Sartori, L. F., et al. 2017, *MNRAS*, 466, 2879
- Bertin, E., & Arnouts, S. 1996, *A&AS*, 117, 393
- Boquien, M., Burgarella, D., Roehly, Y., et al. 2019, *A&A*, 622, A103
- Bradley, L., Sipőcz, B., Robitaille, T., et al. 2022, *astropy/photutils*: v1.4.0, Zenodo, doi:10.5281/zenodo.596036
- Brinchmann, J., Kunth, D., & Durret, F. 2008, *A&A*, 485, 657
- Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, *ApJ*, 533, 682
- Cassata, P., Le Fèvre, O., Charlot, S., et al. 2013, *A&A*, 556, A68
- Chabrier, G. 2003, *PASP*, 115, 763
- De Barros, S., Oesch, P. A., Labbé, I., et al. 2019, *MNRAS*, 489, 2355
- Dey, A., Schlegel, D. J., Lang, D., et al. 2019, *AJ*, 157, 168
- Endsley, R., Stark, D. P., Charlot, S., et al. 2021a, *MNRAS*, 502, 6044
- Endsley, R., Stark, D. P., Chevallard, J., & Charlot, S. 2021b, *MNRAS*, 500, 5229
- Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018, *A&A*, 616, A1
- Gordon, K. D., Bohlin, R., Sloan, G. C., et al. 2022, *AJ*, 163, 267
- Greene, T. P., Kelly, D. M., Stansberry, J., et al. 2017, *JATIS*, 3, 035001
- Hashimoto, T., Laporte, N., Mawatari, K., et al. 2018, *Natur*, 557, 392
- Inoue, A. K. 2011, *MNRAS*, 415, 2920
- Jeřábková, T., Kroupa, P., Dabringhausen, J., Hilker, M., & Bekki, K. 2017, *A&A*, 608, A53
- Jiang, L., Cohen, S. H., Windhorst, R. A., et al. 2020, *ApJ*, 889, 90
- Kennicutt, R. C., & Evans, N. J. 2012, *ARA&A*, 50, 531
- Labbé, I., Oesch, P. A., Bouwens, R. J., et al. 2012, *ApJL*, 777, L19
- Maraston, C., Pforr, J., Henriques, B. M., et al. 2013, *MNRAS*, 435, 2764
- Matthee, J., Sobral, D., Boone, F., et al. 2017, *ApJ*, 851, 145
- Oh, K., Sarzi, M., Schawinski, K., & Yi, S. K. 2011, *ApJS*, 195, 13
- Oke, J. B., & Gunn, J. E. 1983, *ApJ*, 266, 713
- Osterbrock, D. E., & Ferland, G. J. 2006, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei* (Sausalito, CA: Univ. Science Books)
- Pontoppidan, K., Blome, C., Braun, H., et al. 2022, arXiv:2207.13067
- Rasappu, N., Smit, R., Labbé, I., et al. 2016, *MNRAS*, 461, 3886
- Rigby, J., Perrin, M., McElwain, M., et al. 2022, arXiv:2207.05632
- Robertson, B. E. 2022, *ARA&A*, 60, 121
- Schaerer, D. 2002, *A&A*, 382, 28
- Schaerer, D., & de Barros, S. 2009, *A&A*, 502, 423
- Senchyna, P., Stark, D. P., Mirocha, J., et al. 2020, *MNRAS*, 494, 941
- Senchyna, P., Stark, D. P., Vidal-García, A., et al. 2017, *MNRAS*, 472, 2608
- Shibuya, T., Ouchi, M., & Harikane, Y. 2015, *ApJS*, 219, 15
- Shibuya, T., Ouchi, M., Harikane, Y., et al. 2018, *PASJ*, 70, S15
- Shim, H., Chary, R.-R., Dickinson, M., et al. 2011, *ApJ*, 738, 69
- Shivaei, I., Reddy, N. A., Siana, B., et al. 2018, *ApJ*, 855, 42
- Smit, R., Bouwens, R. J., Labbé, I., et al. 2014, *ApJ*, 784, 58
- Smit, R., Bouwens, R. J., Franx, M., et al. 2015, *ApJ*, 801, 122
- Sobral, D., Matthee, J., Darvish, B., et al. 2015, *ApJ*, 808, 139
- Sobral, D., Matthee, J., Brammer, G., et al. 2019, *MNRAS*, 482, 2422
- Stark, D. P., Schenker, M. A., Ellis, R., et al. 2013, *ApJ*, 763, 129
- Tang, M., Stark, D. P., Chevallard, J., & Charlot, S. 2019, *MNRAS*, 489, 2572
- Thomas, D., Steele, O., Maraston, C., et al. 2013, *MNRAS*, 431, 1383
- Whitler, L., Stark, D. P., Endsley, R., et al. 2022, arXiv:2206.05315
- Zou, H., Zhou, X., Fan, X., et al. 2019, *ApJS*, 245, 4