Physical characterization of F090W-dropout galaxies in the Webb’s First Deep Field
SMACS J0723.3−7323

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Submitted to ApJ

ABSTRACT

This paper highlights initial photometric analyses of JWST NIRCam imaging data in the sightline of SMACS0723. We here aim to identify high-redshift galaxy candidates at $z > 7$. We start our analysis with the cluster field, where the extant HST data are available for photometric calibration and additional constraints, and identify three F090W-dropout sources, whose redshifts were recently confirmed in an independent spectroscopic analysis to $z_{\text{spec}} = 7.663, 7.665,$ and 8.499. We then extend our analysis to the parallel field and identify one additional F090W-dropout at photometric redshift of $z_{\text{phot}} = 10.0^{+0.9}_{-1.5}$. The NIRCam F150W images clearly resolve all sources and reveal their sub-galactic components that were unresolved in the previous F160W imaging. Our spectral energy distribution analysis reveals that those galaxies are characterized by young stellar populations with extreme H$\beta$ and [O iii] lines being captured in the F444W band and seen as color excess. We publish the best-fit templates and optical line fluxes of the four galaxies for future reference and spectroscopic follow-up planning.

1. INTRODUCTION

Our exploration in the early universe has been enabled by the Hubble Space Telescope (HST). Since the installation of Wide Field Camera 3 (WFC3), our redshift limit has been pushed toward $z \approx 6$, the era known as the epoch of reionization (Gunn & Peterson 1965; Madau et al. 1999; Robertson et al. 2015). A tremendous amount of efforts has been invested to the photometric search of early galaxies via Lyman break technique (Steidel et al. 1996), revealing hundreds of galaxy candidates from various HST surveys. Spectroscopic followups then have successfully confirmed $\sim 20$ of those candidates at $z > 7$ (e.g., Vanzella et al. 2011; Shibuya et al. 2012; Finkelstein et al. 2013; Stark et al. 2015; Oesch et al. 2015; Hashimoto et al. 2018; Roberts-Borsani et al. 2022b) up to $\sim 12$ (Oesch et al. 2016; Jiang et al. 2021).

The James Webb Space Telescope (JWST) has started revolutionizing our understanding of galaxies and stellar populations in the era. With its exquisite sensitivity coverage up to $\sim 5 \mu m$, NIRCam plays the key role in pushing the redshift front of galaxy search, which enables identification of sources beyond the previous record (Naidu et al. 2022; Castellano et al. 2022) up to $z \gtrsim 20$. Identification of sources at such a redshift range is crucial to our understanding of the formation of the first galaxies and stars (Stiavelli & Trenti 2010; Harikane et al. 2022; Pacucci et al. 2022).

As part of the Early Release Observations (ERO), JWST pointed a field of SMACS0723, a massive galaxy cluster at $z = 0.390$, dubbed as the Webb’s First Deep Field. This observing program, by utilizing all four instruments onboard, provides us a new glimpse of the universe. The new imaging data revealed a number of potentially interesting high-redshift sources both in the cluster center and parallel pointings (Figs. 1 and 2). Here we present our initial identification of galaxy candidates selected via F090W-dropout, ie those at $z > 7$. The simultaneous imaging of the NIRCam’s dual modules allows us to explore early galaxies in two-fold. The first allows us to search for intrinsically faint-but-strongly magnified source by gravitational lensing. The second works as a reference to the cluster field, as well as provides a glimpse of galaxy search with JWST in normal fields. This paper is structured as follows: In Sec. 2, we present our analyses on the JWST ERO data, including flux calibration by using well-calibrated HST data. We present our selection methodology of high-$z$ sources in Sec. 3 and the final candidate galaxies and their properties in Sec. 4. In Sec. 5, we discuss future investigations and summarize our results. Through-
Table 1. 5σ-limiting magnitudes.

| ID       | WDF-C | WDF-P |
|----------|-------|-------|
| NIRCAM F090W | 27.76 | 27.96 |
| NIRCAM F150W | 27.82 | 28.20 |
| NIRCAM F200W | 27.95 | 28.39 |
| NIRCAM F277W | 28.18 | 28.71 |
| NIRCAM F356W | 28.43 | 28.71 |
| NIRCAM F444W | 28.37 | 28.30 |
| ACS F435W    | 26.72 | –     |
| ACS F606W    | 27.45 | –     |
| ACS F814W    | 26.96 | –     |
| WFC3 F105W   | 27.51 | –     |
| WFC3 F125W   | 27.36 | –     |
| WFC3 F140W   | 27.55 | –     |
| WFC3 F160W   | 27.36 | –     |

Note—WDF-C and WDF-P represent cluster and parallel fields, respectively.

out, we adopt the AB magnitude system (Oke & Gunn 1983; Fukugita et al. 1996), cosmological parameters of Ω_m = 0.3, Ω_Λ = 0.7, H_0 = 70 km s^{-1} Mpc^{-1}, and the Chabrier (2003) initial mass function.

2. DATA AND ANALYSES

2.1. JWST Early Release Observations Program

We base our primary analysis on the data taken as part of the JWST Early Release Observations Program, in the sightline of SMACS0723. The NIRCam imaging data consist of F090/150/200/277/356/444W filters, with ~2 hr exposure on each. The photometric magnitude limits, measured in our photometric process below, are listed in Table 1.

We retrieve detector-corrected data (.rate.fits) from a dedicated AWS storage placed by the MAST team at STScI. We then reduce those images by using the official pipeline (ver.1.6.0) for photometric calibration (IMAGE STEP2) and combining in a common pixel grid (IMAGE STEP3). During the step, we include one extra step to subtract 1/f-noise in .cal.fits images by using bbpn, by following the procedure presented in (Schlawin et al. 2021). The final pixel scale is set to 0.0315.

Images are aligned to the common astrometric WCS in multiple steps. First, we align the single F444W image to the GAIA-DR3 wcs frame. The rest of the NIRCAM images are then aligned to the F444W image, by using both point and compact galaxies. We finally refine the pixel grid of all images in the one of F444W, by using a resampling module of reproject.

To homogenize the PSF of the NIRCam images to the F444W PSF size, we generate convolution kernels by following the same procedure in (Morishita 2021). Bright stars are identified by cross matching with the source catalog and the GAIR DR3 catalog. We visually inspect each of them and exclude those saturated or contaminated by neighboring objects. We then resample each PSF to align those at sub-pixel grid and stacked all stars in each filter to generate a median PSF. We then provide the median stars to pypher (Boucaud et al. 2016), to generate convolution kernels for each filter. The quality of convolved PSFs is excellent, with ≲ 1% agreement in the encircled flux at r = 0.′16, within which our photometric fluxes are extracted.

We also utilize the HST data available in the cluster field, originally taken in the RELICS program (Coe et al. 2019; Salmon et al. 2020), to supplement our selection. We retrieve raw data from MAST, that consist of seven filters (F435/606/814/105/125/140/160W) and reduce those by using borgpipe (Morishita 2021). It is noted that there is no HST coverage in the parallel field. For HST images, we repeat a similar analysis as for NIRCam, but convolve images to the WFC3-IR F160W PSF, which has a similar FWHM as in F444W. This choice was made because of significantly different PSF shapes in JWST and HST images. While this may leave systematic offsets between the two instruments, those will be removed in the following analysis (Sec.2.2).

For photometric flux extraction, we run borgpipe, a photometric pipeline designed for HST and JWST data reduction and photometric analyses. borgpipe runs SExtractor (ver.2.25.0; Bertin & Arnouts 1996) for image detection and flux extraction, while it includes extra steps for sophisticated error estimate of images, aperture correction, and Lyman-break dropout selection of high-z candidates, as done in similar previous studies (Trenti et al. 2012; Morishita et al. 2018a). We use infrared stack of F200/277/356/444W filters as a detection image for both fields.

One major update in our photometric process in this study is made to enhance detection near bright stars. For those regions, while we visually confirm the

1 https://outerspace.stsci.edu/display/MASTDATA/JWST-AWS-Bulk-Download+Scripts
2 https://github.com/mtakahiro/bbpn
3 https://reproject.readthedocs.io/en/stable/
Figure 1. The composite RGB image of the Webb’s First Deep Field, in the sightline of SMACS0723 (cluster field). The JWST NIRCam and HST ACS and WFC3-IR images are combined (blue: F435W+F606W+F814W+F090W+F105W, green: F125W+F140W+F150W+F200W, red: F277W+F356W+F444W). The final F090W-dropout candidates (Sec. 4.1) are marked.

presence, SExtractor does not detect some compact sources. We thus add an extra step to mask out bright stars, their diffraction spikes, and bright cluster galaxies. To make a mask, we run SExtractor with less aggressive deblending and large background area, so it captures extended spikes of bright stars and faint diffuse light of bright galaxies. We visually inspect the detection segmentation map and manually exclude those belong to the bright objects. We then run SExtractor this time with more aggressive detection configuration (smaller detection area, smaller background size), to detect small sources in the background of the cluster.

2.2. Zero-point correction across filters and instruments

Next, we aim to calibrate flux zeropoints of imaging data by using eazypy, a python wrapper of photometric redshift code EaZY (Brammer et al. 2008). To correct magnitude zeropoint offset, we run redshift fitting on those with spectroscopic redshifts listed in Mahler et al. (2022), both cluster member galaxies and lensed emission line galaxies. This process is at first applied sepa-
Figure 2. The parallel field of the Webb’s First Deep Field. The JWST NIRCam images are combined (blue: F090W, green: F150W, red: F277W+F356W+F444W). The final F090W-dropout candidate (Sec. 4.1) is marked.

rately for HST and NIRCam images, to correct relative offset among the filters within each instrument. The correction is 10% relative to F150W for NIRCam filters and a few % to F160W for HST filters. We then correct the relative offset between the two instruments, by scaling the observed NIRCam F150W fluxes to the one interpolated from the observed fluxes in HST F140W and F160W filters. We use bright and isolated objects with $S/N > 20$ taken from the photometric catalog constructed above. For interpolation, we assume a linear slope between those two filters. We adopt the median of correcting factors, 0.66. Lastly, we rerun eazypy but this time including all filters for fine tuning. The derived correction factor is 30–40% in the NIRCam filters (in the sense of NIRCam being more sensitive), which is consistent with those in Rigby et al. (2022) but our correction is larger by a factor of $\sim 1.5$ to 2. This potentially reflects the fact that our calibration here is relative to the measurements in HST images, which may include additional systematics such as aperture correction in our PSF-matching processing. We apply the correction to the photometric catalog and treat this as a final catalog. For the NIRCam images in the parallel field, where no spectroscopic measurement or HST images are avail-
3. SELECTION OF HIGH-Z GALAXY CANDIDATES

In what follows, we present our selection process of galaxy candidates at $z \gtrsim 7$. Our selection method consists of three steps — Lyman break color selection, photometric redshift analysis, and visual inspection. To give a summary, we identify 22 (42) in the first step; exclude 18 (38) in the second step; and then exclude 1 (3) in the final step in the cluster (parallel) field. The final candidates are shown in Fig. 4. Those excluded in those steps are presented in Appendix and Table 5.

3.1. F090W-Dropout Selection

We select candidate high-$z$ galaxies with the following selection cut:

\[
S/N_{F090} > 6.0 \\
m_{090} - m_{150} > 2.0 \\
m_{150} - m_{200} < 0.2 \\
S/N_{F090} < 2.0
\]

(Fig. 3). While we require non-detection in F090W ($z$-band dropout), we calculate the color of Lyman break by using the flux upper limit estimated in the image in the photometric step above. For the cluster field, where HST images are available, we supplement the selection by adding F435/606/814W as non-detection filters. The color boundary of the selection is designed to effectively capture young, relatively dust-free galaxies at $7 \lesssim z \lesssim 10.5$. In Fig. 3, we show the colors of a single power-law slope for different UV $\beta_{\lambda}$ ($-1.5$, $-2.0$, and $-2.5$). This selection at the same time effectively minimizes low-$z$ interlopers, such as foreground dwarfs and low-$z$ galaxy populations. Colors of dwarf stars, taken from the IRTF spectral library (Rayner et al. 2003) and the SpeX prism library (Burgasser 2014) are shown. Their color distribution is scattered applying a random 0.1 photometric error to each template for 100 times. Colors of lower-$z$ galaxies at $0.5 < z < 4.5$ are also shown.

3.2. Photometric redshift selection

We apply photometric redshift cut to those selected in the previous section, in a similar same way as done in previous work (Morishita et al. 2018a; Roberts-Borsani et al. 2022a; Ishikawa et al. 2022). This is to minimize the fraction of low-$z$ interlopers such as galaxies with old stellar populations (e.g., Oesch et al. 2016) and foreground dwarfs (e.g., Morishita et al. 2020) that may migrate to the color boundary box due to photometric scatters. We run EaZY with the default magnitude prior set to the observed F150W magnitude. The redshift range is

![Figure 3. Final F090W-dropout sample (red circles with arrow) in color-color space. All sources are not detected in F090W and thus the F090W − F150W color is lower limit. Sources at various redshifts are also shown — young galaxies with different UV $\beta_{\lambda}$ slopes (purple squares), low-$z$ galaxies of old (red diamonds), and foreground dwarfs (gray dots).](image-url)
set as $0 < z < 20$, with a step size of $\log_{10}(1 + z) = 0.01$. We exclude those with $p(z < 6.5) > 0.2$, i.e. total redshift probability at $z < 6.5$ is greater than 20%.

3.3. Visual Inspection

Lastly, we visually inspect the sources remained after the previous two steps. In this step, we discard those near the diffraction spikes or possible artifacts, such as flux residuals of snowballs (Rigby et al. 2022). Sources are excluded when either of the inspectors (TM, MS) raises a flag that the object is an obvious artifact, blending with bright sources (where flux measurement would be challenging), or shows significant amount of positive pixels in the non-detection filters (but is not detected at $S/N > 2$). We also identify two unresolved sources that show reasonable fit with dwarf templates. These objects locate at the right bottom of the selection boundary in Fig. 3 and are possibly foreground stars. While those unresolved point-like sources could be a potential quasar candidates (e.g., Morishita et al. 2020; Fujimoto et al. 2022), for purity of sample we exclude both objects in this step.

4. RESULTS

The final sample consists of 3 candidates in the cluster field and 1 in the parallel field. In what follows, we provide an overview of those galaxies, and then conduct spectral energy distribution (SED) analysis to characterize their physical properties.

4.1. Overview of selected candidate galaxies

In Fig. 4, we show postage stamps of those in the cluster field. In addition to their clear dropout in the F090W band, those galaxies are not detected in the optical filters of HST. Indeed, all three galaxies are spectroscopically confirmed in recent work by Carnall et al. (2022), to $z = 7.663$ (hereafter ZD1), 7.665 (ZD2), and 8.498 (ZD3). Our redshift estimate is skewed toward higher redshifts (Table 5) but still consistent with their spectroscopic redshift, which assures the quality of our photometric catalog and clean sample selection.

The comparison of the NIRCam images to WFC3-IR images clearly showcases the resolving power of JWST. Aside multi-band postage stamps above, in Fig. 5 we also show the zoom-in image of each candidates in WFC3 F160W and NIRCam F150W. The NIRCam images resolve all candidates and reveal their morphology in detail in rest-frame UV ($\sim 0.15 \mu m$ in F090W) to optical ($\sim 0.44 \mu m$ in F444W). Lens magnification of the sources in the cluster fields ($\mu \sim 1.6, 2.9, and 10.1$, respectively; Oguri 2010; Carnall et al. 2022) further allows us to reveals further details down to sub-galactic scale.

ZD1 is isolated and apart from other neighboring sources. The source consists of one primary core and small component to its right. To provide a detailed view of this sub component, we perform single component Sérsic fit in the F150W image by using galfit (Peng et al. 2002). We clearly see the residual component in the residual image. Detailed light profile modeling is deferred to future work. In the stamp of ZD2, there are two sources to the lower-right direction but they are faint and reasonably apart from ZD2, and their flux contamination to ZD2 is considered small. Same as for ZD1, single Sérsic fit reveals multiple components, including a diffuse extended component. ZD3 has two compact companions that align in one direction. SExtractor successfully deblends each of the three sources. Among the three sources, ZD3 is the brightest and thus the flux...
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Contamination is also considered as small. Indeed, Sérsic fit to ZD3, with the two close companions included simultaneously, reveals cleaner residual compared to the other two. Thus, ZD3 is characterized as compact, despite its high magnification. We present the measured sizes in Table 3. The middle component (ID 3333 in the segmentation map of Fig. 4) exhibits similar dropout color as for ZD3. However, we find that this object is detected in F105W, whereas ZD3 is undetected in the same band. In addition, while uncertainty is large, photometric redshift of this object is $z \sim 2.3$. We thus conclude that, despite the similarity in color, this object is not likely at similar redshift.

It is worth noting that ZD3 was not detected in the public catalog by the RELICS team\(^4\). ZD1 and ZD2 are detected and listed in the RELICS catalog (IDs 356 and 1138) but with photometric redshift of $z \sim 3.4$ and $4.7$. Thus, none of the three spectroscopically confirmed galaxies was identified as a candidate high-$z$ source from the HST-only dataset.

In the bottom panel of Fig. 4, we show the F090W-dropout galaxy identified in the parallel field, ZD4. Given that the selection is made with 6 NIRCam filters, one of which (F090W) is for non-detection, careful inspection in its SED distribution and F090W images is essential. ZD4 is characterized with photometric redshift of $z_{\text{phot}} \sim 10.0_{-1.3}^{+0.9}$. While the photometric redshift distribution has a relatively wider range, the solution is unique to high-$z$ solution, with $p(z < 6.5) \sim 1\%$. ZD4 shows extended morphology, elongated to the vertical direction. Interestingly, it shows two separate components in the F150W and F200W filters, which offer the highest resolution among the filters, while it is barely separated in the long channel of NIRCam. Since our detection is based on the F444W image, these (possible) two components are not deblended in our catalog.

A caveat about this source is its location near two bright sources—one at $\sim 0''7$ and brighter one at $\sim 1''5$ separation (possibly the host galaxy of the former). The aperture used for flux extraction, however, is small enough ($r = 0''16$), and thus the measured colors should be minimally affected by those foreground objects.

4.2. Spectral energy distribution fitting

To investigate the physical properties of the selected candidates, we here conduct spectral energy distribution fitting. We use gsf\(^5\) (Morishita et al. 2018b, 2019) to obtain properties such as stellar masses and rest-frame colors. For those with spec-$z$, we fix redshift to those during fitting. For ZD4, we set redshift as a free parameter within the 16-84th percentile range derived by EaZY. We use a template library generated by fsp$s$ (Conroy et al. 2009), with the Calzetti et al. (2000) dust attenuation law. We adopt a non-parametric form for our star formation modeling. As presented in Morishita et al. (2019); Morishita (2021), this form allows flexibility in shape of star formation and provides clear insight in the stellar populations that consists of the target SED. During our initial test, we found that inclusion of emission lines is crucial to successfully fit the observed fluxes. We add an emission component to our fitting model, with two free parameters, ionization parameter, $\log U \in [-3 : -1]$, and its amplitude.

In Fig. 6, we show the results of SED fit. All galaxies are well-fitted with young stellar populations, with significant contributions from emission lines. For galaxies at $z < 9$, strong emission lines such as $[\text{O} \text{iii}]$ doublet and H$\beta$ fall in the wavelength range of F444W (and $[\text{O} \text{ii}]$ in F356W for ZD2). The observed excess in the

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\(^4\) https://relics.stsci.edu
\(^5\) https://github.com/mtakahiro/gsf
$m_{F356W} - m_{F444W}$ color of those galaxies clearly indicates intense star formation and hot ISM (e.g., Roberts-Borsani et al. 2020; Morishita et al. 2020) and provide clues to metallicity (e.g., Schaerer et al. 2022). While direct inference of their emission properties is not achievable here, the observe blue UV slope is large in negative and suggestive of their young nature (Bouwens et al. 2014; Yamanaka & Yamada 2019). For future followup planning, we derive fluxes of optical emission lines by using the best-fit templates and present those in Table 4.

5. DISCUSSION AND SUMMARY

Already on the basis of this first data set it is clear that detections with WFC3-IR with few bands shorter than 1.6 $\mu$m are not a robust way to identify high-$z$ galaxies as the two sources in the cluster field had been assigned much lower redshifts. These data also allow us to begin testing the reliability of photo-$z$ at previously untested redshifts. More will be needed but it is comforting that all three candidates identified in the cluster field on the basis of photometry alone were spectroscopically confirmed. This gives us hope that photometric selection is not seriously plagued by false detection. We cannot say at this time anything about its completeness given that the NIRSpec MSA slits were not placed on the initially selected (but then rejected) dropout objects.

We repeated the selection analyses for the cluster field with the NIRCam imaging data only. This provided us the same set of the F090W-dropout galaxies selected in the first step of Sec 3.1. This implies that our selection of candidates in the parallel field, despite the absence of HST coverage, is more or less of similar quality. This is also encouraging for future search of high-$z$ sources with JWST alone (e.g., pure-parallel imaging programs).

A final note is that our analysis may still not be complete in terms of source detection. As mentioned above, the (in)famous hexagonal PSF spikes from bright stars severely contaminate some fraction of surrounding pixels and make it challenging to detect all background sources. While our efforts by masking those affected pixels significantly improved the detection completeness, there are still a small amount of possible sources being missed from our detection. In addition, the cluster field is even more challenging, being affected by brightest cluster galaxies. For such crowded fields, a dedicated analysis (e.g., Bouwens et al. 2021) will be required. Therefore, we defer advanced analysis, such as inference of the UV luminosity function, to future work.

SMACS0723 is not only the deepest NIR imaging field at this time, but also has rich spectroscopic data obtained by NISPEC and NIRISS as well as mid-IR imaging by MIRI collected during the ERO campaign. Future followup study with those dataset will further reveal the nature of the three galaxies in the cluster field. While the additional candidate newly identified in this study is not exceptionally bright as those in the cluster field, but still within the reach of sensitive NIRSPEC spectroscopy for its strong emission lines revealed in our study. For future spectroscopic study and planning, we publish line fluxes of the four final galaxies measured with the best-fit templates in Table 4. The best-fit templates will be published on a dedicated website.

ACKNOWLEDGEMENTS

The Early Release Observations and associated materials were developed, executed, and compiled by the ERO production team: Hannah Braun, Claire Blome, Matthew Brown, Margaret Carruthers, Dan Coe, Joseph DePasquale, Néstor Espinoza, Macarena García Marin, Karl Gordon, Alaina Henry, Leah Hustak, Andi James, Ann Jenkins, Anton Koekemoer, Stephanie LaMassa, David Law, Alexandra Lockwood, Amaya Moro-Martín, Susan Mullally, Alyssa Pagan, Dani Player, Klaus Pontoppidan, Christine Pulliam, Leah Ramsay, Swara Ravindranath, Neill Reid, Massimo Robberto, Elena Sabbi, Leonardo Ubeda. The EROs were also made possible by the foundational efforts and support from the JWST instruments, STScI planning and scheduling, and Data Management teams. TM is grateful to Guido Roberts-Borsani, Benedetta Vulcani, and Xin Wang for our constructive discussion at UCLA and their insights into the new dataset from this brand new observatory, and Tommaso Treu for his kind and generous support.

APPENDIX A

In Table 5, we present all F090W-dropout sources selected in Sec. 3.1, with comments on the reason of rejection if the source is excluded in the final sample.

In Fig. 7, we show the two unresolved dropouts. While both exhibit clear dropout color in F090W-F150W, our SED fitting analysis with dwarf templates indicates that these are likely foreground stars.
Figure 6. SED fitting results from gsf. Redshift is fixed for for the spec-z confirmed objects during fit, while left as a free parameter for the rest objects. Photometric redshift distribution of ZD4 is shown in its inset. The best-fit templates will be published at https://mtakahiro.github.io.

Table 3. Coordinates and physical properties of the F090W-dropout candidates.

| ID  | R.A.  | Decl. | z    | MUV  | log M* | SFR  | µ   | r_e  | n  |
|-----|-------|-------|------|------|--------|------|-----|------|----|
|     | degree | degree |      | ABmag|        |       |     |      |     |
| ZD1 | 110.8339 | -73.43452 | 7.66 | -20.42±0.06 | 8.38±0.15 | 1.34±0.48 | 1.6 | 3.01±0.07 | 1.32±0.14 |
| ZD2 | 110.84448 | -73.43505 | 7.67 | -20.90±0.05 | 7.65±1.08 | 1.06±1.02 | 2.7 | 5.07±0.17 | 0.37±0.07 |
| ZD3 | 110.85937 | -73.44914 | 8.50 | -19.82±0.11 | 8.70±0.29 | 2.56±2.55 | 10.1 | 2.25±0.09 | 0.20±0.13 |
| ZD4 | 110.79638 | -73.446976 | 9.88±0.69 | -19.22±0.13 | 9.04±0.81 | 0.54±3.62 | 0.47 | 2.17±0.23 | 1.81±0.58 |

Note—†: photometric redshift derived by gsf. µ: effective radius. Pixel plate scale is 0.0315. n: Sérsic index. Measurements are not corrected for magnification factor, µ.

Table 4. Optical emission line fluxes of the sample (candidate) galaxies at 7.6 < z < 11.

| id  | Lyα | [OII]3728 | Hβ| [OIII]4959/Hβ | [OIII]5007 | [NII]6583 | [SII]6725 |
|-----|-----|----------|---|--------------|------------|----------|----------|
| ZD1 | 2341 | 2.9 | 159 | 59 | 110 | 5.4 | 235 | 253 | 1017 | 11 | 374 | 27 | 84 | 90 |
| ZD2 | 4411 | 1.0 | 356 | 1469 | 240 | 449 | 29 | 1006 | 1130 | 45 | 1835 | 96 | 381 | 68 |
| ZD3 | 5903 | 3.0 | 427 | 120 | 37 | 79 | 5 | 150 | 132 | 53 | 278 | 6 | 32 | 3 |
| ZD4 | 2301 | 1.5 | 313 | 41 | 88 | 181 | 6 | 36 | 36 | 113 | 92 | 22 | 10 | 10 | 20 |

Note—Fluxes are in units of 10⁻²⁰ erg s⁻¹ cm⁻². Uncertainties are calculated based on the 16/84th percentile range of the best-fit templates from gsf. Fluxes are not corrected for magnification. The full templates will be published at https://github.com/mtakahiro.

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### Table 5. F090W-dropout candidates

| ID     | R.A.       | Decl.       | $m_{F150W}$ | $z_{\text{phot}}$ | $p(z > 6.5)$ | Comments |
|--------|------------|-------------|-------------|-------------------|--------------|----------|
|        | degree     | degree      | mag         |                   |              |          |
| WDF-C-601 | 110.7823486 | -73.4423676 | 27.3        | $1.77^{+0.37}_{-0.78}$ | 0.09         | phot-z   |
| WDF-C-939 | 110.8339005 | -73.4345169 | 26.8        | $10.11^{+0.25}_{-0.34}$ | 1.00         | ZD1      |
| WDF-C-1094 | 110.7722702 | -73.4480362 | 27.0        | $1.74^{+0.12}_{-0.43}$ | 0.01         | phot-z   |
| WDF-C-1120 | 110.7754433 | -73.4482651 | 26.7        | $1.71^{+0.17}_{-1.49}$ | 0.00         | phot-z   |
| WDF-C-1168 | 110.7665024 | -73.4502640 | 26.7        | $2.13^{+0.24}_{-0.64}$ | 0.04         | phot-z   |
| WDF-C-1184 | 110.7634506 | -73.4505463 | 27.6        | $1.92^{+0.49}_{-0.48}$ | 0.06         | phot-z   |
| WDF-C-1237 | 110.8444824 | -73.4350510 | 26.3        | $10.01^{+0.48}_{-0.51}$ | 1.00         | ZD2      |
| WDF-C-1349 | 110.8459930 | -73.4354706 | 27.5        | $2.11^{+0.65}_{-0.64}$ | 0.01         | phot-z   |
| WDF-C-1462 | 110.8468399 | -73.4366074 | 27.2        | $1.70^{+0.47}_{-0.41}$ | 0.02         | phot-z   |
| WDF-C-1616 | 110.8176956 | -73.4335349 | 27.7        | $0.86^{+0.79}_{-0.79}$ | 0.39         | phot-z   |
| WDF-C-2051 | 110.7814026 | -73.450329  | 27.3        | $1.90^{+0.58}_{-0.58}$ | 0.03         | phot-z   |
| WDF-C-2104 | 110.7932739 | -73.4523697 | 26.5        | $0.44^{+0.55}_{-0.30}$ | 0.00         | phot-z   |
| WDF-C-2499 | 110.8226471 | -73.4495444 | 27.7        | $0.57^{+0.34}_{-1.20}$ | 0.01         | phot-z   |
| WDF-C-2537 | 110.8063003 | -73.4543866 | 27.7        | $0.38^{+0.55}_{-0.26}$ | 0.00         | phot-z   |
| WDF-C-2651 | 110.8042603 | -73.4546280 | 26.5        | $2.62^{+0.66}_{-0.66}$ | 0.47         | phot-z   |
| WDF-C-2958 | 110.7722702 | -73.4637070 | 26.7        | $1.85^{+0.41}_{-1.09}$ | 0.04         | phot-z   |
| WDF-C-3337 | 110.8593674 | -73.4491425 | 27.4        | $9.33^{+0.56}_{-0.47}$ | 1.00         | ZD3      |
| WDF-C-3361 | 110.8234406 | -73.4565887 | 26.5        | $1.96^{+0.16}_{-0.11}$ | 0.00         | phot-z   |
| WDF-C-3679 | 110.8136215 | -73.4602756 | 26.9        | $1.38^{+0.57}_{-0.57}$ | 0.00         | phot-z   |
| WDF-C-4336 | 110.8320389 | -73.4618301 | 26.9        | $1.87^{+0.57}_{-0.57}$ | 0.00         | phot-z   |
| WDF-C-4400 | 110.8778305 | -73.4530716 | 27.5        | $0.50^{+0.29}_{-0.22}$ | 0.00         | phot-z   |
| WDF-C-5626 | 110.8316004 | -73.4693146 | 27.6        | $0.52^{+1.02}_{-0.35}$ | 0.00         | phot-z   |

**Note.** For those excluded from the final sample, we provide the reason for rejection in the last column.

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![Figure 7](image-url)  
**Figure 7.** Postage stamps of two possible dwarfs.
### Table 6.  (Continued) F090W-dropout candidates

| ID      | R.A.   | Decl.  | m\(_{F150W}\) | z\(_{\text{phot.}}\) | p(z > 6.5) | Comments       |
|---------|--------|--------|--------------|----------------|------------|----------------|
|         | degree | degree | mag          |                |            |                |
|         |        |        |              |                |            |                |
| Parallel Field |
| WDF-P-300  | 110.6504669 | -73.4660416 | 26.9 | 7.06^+1.99 | 0.58 | phot-z         |
| WDF-P-345  | 110.6363297 | -73.4693375 | 27.7 | 2.51^+1.08 | 0.16 | phot-z         |
| WDF-P-425  | 110.6682739 | -73.4636917 | 27.7 | 2.34^+0.32 | 0.47 | phot-z         |
| WDF-P-662  | 110.6907730 | -73.4610367 | 28.2 | 6.64^+0.14 | 0.73 | phot-z         |
| WDF-P-731  | 110.6330109 | -73.4729767 | 27.1 | 1.83^+1.74 | 0.00 | phot-z         |
| WDF-P-825  | 110.6522141 | -73.4699173 | 26.6 | 3.18^+1.01 | 0.46 | phot-z         |
| WDF-P-1016 | 110.6618042 | -73.4695892 | 27.3 | 2.24^+0.28 | 0.21 | phot-z         |
| WDF-P-1027 | 110.6666666 | -73.4806061 | 27.4 | 7.16^+2.04 | 0.55 | phot-z         |
| WDF-P-1043 | 110.6965577 | -73.4627457 | 27.8 | 1.98^+0.35 | 0.03 | phot-z         |
| WDF-P-1069 | 110.6358719 | -73.4749603 | 27.0 | 2.36^+0.87 | 0.31 | phot-z         |
| WDF-P-1511 | 110.6462250 | -73.4758911 | 28.0 | 9.98^+0.93 | 0.99 | ZD4           |
| WDF-P-1690 | 110.6534729 | -73.4756317 | 27.8 | 2.00^+0.22 | 0.00 | phot-z         |
| WDF-P-1781 | 110.6123123 | -73.4845581 | 26.2 | 2.12^+0.23 | 0.11 | phot-z         |
| WDF-P-1845 | 110.7110672 | -73.4653168 | 27.7 | 8.93^+0.64 | 0.67 | phot-z         |
| WDF-P-1869 | 110.6317139 | -73.4814301 | 27.9 | 0.54^+0.40 | 0.00 | phot-z         |
| WDF-P-1935 | 110.6832521 | -73.4715500 | 27.6 | 1.96^+0.35 | 0.00 | phot-z         |
| WDF-P-2190 | 110.6209564 | -73.4860764 | 27.0 | 9.75^+1.04 | 0.77 | phot-z         |
| WDF-P-2419 | 110.6621094 | -73.4796295 | 27.0 | 6.70^+1.10 | 0.54 | phot-z         |
| WDF-P-2595 | 110.6961136 | -73.4741974 | 28.2 | 9.13^+1.15 | 0.86 | likely dwarf   |
| WDF-P-2754 | 110.6839523 | -73.4780655 | 27.9 | 2.67^+0.83 | 0.24 | phot-z         |
| WDF-P-3062 | 110.6464157 | -73.4875107 | 27.5 | 2.01^+0.27 | 0.05 | phot-z         |
| WDF-P-3215 | 110.7244720 | -73.4731827 | 27.4 | 2.56^+0.99 | 0.30 | phot-z         |
| WDF-P-3461 | 110.7159882 | -73.4769091 | 27.7 | 9.36^+1.52 | 0.96 | likely dwarf   |
| WDF-P-3810 | 110.6612854 | -73.4898376 | 27.8 | 2.33^+0.55 | 0.24 | phot-z         |
| WDF-P-3816 | 110.6615829 | -73.4899139 | 27.4 | 2.48^+0.80 | 0.37 | phot-z         |
| WDF-P-4018 | 110.6829984 | -73.4873352 | 27.7 | 1.94^+0.33 | 0.00 | phot-z         |
| WDF-P-4059 | 110.7155533 | -73.4812851 | 27.3 | 2.55^+0.88 | 0.30 | phot-z         |
| WDF-P-4227 | 110.6610458 | -73.4931030 | 27.8 | 2.33^+0.77 | 0.43 | phot-z         |
| WDF-P-4490 | 110.7154236 | -73.4838257 | 27.7 | 1.87^+0.47 | 0.01 | phot-z         |
| WDF-P-4457 | 110.7171783 | -73.4840775 | 27.2 | 2.19^+0.47 | 0.30 | phot-z         |
| WDF-P-5051 | 110.7789536 | -73.4855957 | 26.8 | 10.18^+0.42 | 1.00 | positive fluxes in F090W |
| WDF-P-5234 | 110.7356110 | -73.4875641 | 27.6 | 2.28^+0.89 | 0.12 | phot-z         |
| WDF-P-5357 | 110.6566544 | -73.5016479 | 26.7 | 1.99^+0.25 | 0.00 | phot-z         |
| WDF-P-5461 | 110.7331696 | -73.4878387 | 27.3 | 7.99^+2.07 | 0.52 | phot-z         |
| WDF-P-5632 | 110.6667633 | -73.4978256 | 27.6 | 1.77^+1.59 | 0.51 | phot-z         |
| WDF-P-5669 | 110.7320099 | -73.4933014 | 27.4 | 2.14^+0.43 | 0.11 | phot-z         |
| WDF-P-5699 | 110.7513504 | -73.4801331 | 27.7 | 2.29^+0.64 | 0.23 | phot-z         |
| WDF-P-5892 | 110.7624817 | -73.4844666 | 27.2 | 1.93^+0.42 | 0.02 | phot-z         |
| WDF-P-5906 | 110.7619171 | -73.4845123 | 26.7 | 2.00^+0.21 | 0.00 | phot-z         |
| WDF-P-6039 | 110.7160568 | -73.4889450 | 27.0 | 2.26^+0.17 | 0.00 | phot-z         |
| WDF-P-6106 | 110.7475204 | -73.4874649 | 27.5 | 7.42^+1.95 | 0.61 | phot-z         |
| WDF-P-6401 | 110.7611389 | -73.4845276 | 27.8 | 2.00^+0.24 | 0.00 | phot-z         |

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