Spectroscopy from Photometry

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Abstract

We use JWST/NIRCam medium band photometry in a single pointing of the Canadian NIRISS Unbiased Cluster Survey to identify 118 extreme emission-line galaxies (EELGs) over 1.7 ≤ z ≤ 6.7, selected using a set of color cuts that target galaxies with extreme [O III] + Hβ and Hα emission. We show that our medium band color selections are able to select galaxies based on emission-line EW, which is advantageous to more commonly used selections since it does not require strong continuum emission, and can select galaxies with faint or red continuum fluxes. The median EWs of our sample is EW(Hα) = 893 Å and EW([O III] + Hβ) = 1255 Å and includes some objects with EW ([O III] + Hβ) ~ 3000 Å. These systems are mostly compact with low stellar mass (median log(M*/M⊙) = 8.03), low metallicity (median Z = 0.14 Z⊙), little dust (median AV = 0.18 mag), and high SSFR (median SSFR = 1.18 × 10−8 yr−1). Additionally, galaxies in our sample show increasing EW(Hα) and EW([O III] + Hβ) with redshift, an anticorrelation of EW(Hα) with stellar mass, and no correlation between EW([O III] + Hβ) and stellar mass. Finally, we present NIRSpec spectroscopy of 15 of the EELGs in our sample. These spectra confirm the redshifts and EWs of the EELGs calculated from the medium bands, which demonstrates the accuracy and efficiency of our color selections. Overall, we show that there are significant advantages to using medium band photometry to identify and study EELGs at a wide range of redshifts.

Unified Astronomy Thesaurus concepts: Emission line galaxies (459); Starburst galaxies (1570); High-redshift galaxies (734); James Webb Space Telescope (2291)

Supporting material: animation

1. Introduction

Extreme emission-line galaxies (EELGs) have become a major field of study in recent years, with many searches targeting EELGs in the local Universe up to high redshifts (e.g., local Universe, Cardamone et al. 2009; Henry et al. 2018; Liu et al. 2022; intermediate z, van der Wel et al. 2011; Maseda et al. 2014, 2018; Tang et al. 2019; Onodera et al. 2020; Tran et al. 2020; Rosenwasser et al. 2022; Boyett et al. 2022; Gupta et al. 2023; high z, Stark et al. 2013; Smit et al. 2014; Roberts-Borsani et al. 2016; Stark et al. 2017; Endsley et al. 2021; Kashino et al. 2023; Mattei et al. 2023; Asada et al. 2023; Laporte et al. 2023; Williams et al. 2023; Rinaldi et al. 2023; Ning et al. 2023). Regardless of their redshift, EELGs are characterized by high equivalent-width (EW) UV-optical emission lines driven by elevated star formation, generally found in low-mass, metal-poor galaxies with little dust. While there is no universal definition, systems with emission-line EW ≥ 100 Å are typically considered EELGs. However, this definition varies widely and is often dependent on redshift.

It is currently presumed that strongly star-forming galaxies are the main drivers of hydrogen reionization over 5.5 ≤ z ≤ 15 (e.g., Robertson et al. 2015; Stefanon et al. 2022), which serves to motivate many of the searches for high-z EELGs. While not all star-forming galaxies can be classified as EELGs, they are abundant at high z (Stark et al. 2013; Smit et al. 2014) and may play an important role during the Epoch of Reionization (EoR). With the beginning of JWST’s science operations, it is now possible to more fully characterize the population of EELGs up to z ~ 9 with NIRCam and NIRSpec. This includes studies of EELGs in the EoR, as well as at intermediate z (z ≤ 5). These lower-z EELGs can serve as analogs to high-z star-forming galaxies and can provide valuable insights on the high-z
population, even in the era of JWST (e.g., Mingozzi et al. 2022; Tang et al. 2022; Rhoads et al. 2023).

Early JWST studies of EELGs have already begun to yield interesting results. These include the identification of very high EW systems (EW > 1000 Å for [O III] + Hβ and Hα) up to z ~ 9 and confirmation that EELGs are common in the high-z Universe (e.g., Kashino et al. 2023; Laporte et al. 2023; Matthee et al. 2023; Rinaldi et al. 2023; Williams et al. 2023). Other work has shown that the hydrogen-ionizing photon-production efficiencies (Ω_{cen}) of high-z EELGs are generally high, as expected if these objects are responsible for reionization (e.g., Asada et al. 2023; Sun et al. 2023).

Additionally, there have been several spectroscopic studies on the physical conditions of the interstellar medium, which find line ratios similar to what is seen in at intermediate redshifts, and low metallicities (e.g., Trump et al. 2023; Taylor et al. 2022).

Many of the searches for EELGs select samples using either broadband photometry (e.g., Stark et al. 2013; Onodera et al. 2020) or wide-field slitless spectroscopy (WFSS; e.g., Maseda et al. 2014, 2018; Kashino et al. 2023 (EIGER), Boyett et al. 2022 (GLASS)). However, while less common, medium-band photometry can provide a powerful tool in the search for EELGs (e.g., Laporte et al. 2023; Terao et al. 2022; Gupta et al. 2023; Williams et al. 2023). The medium bands provide a finer wavelength sampling of galaxy spectral energy distributions (SEDs) than the broad bands, thus offering improved estimates of galaxy properties (e.g., Roberts-Borsani et al. 2021; G. T. E. Sarrouh et al. 2023, in preparation). Additionally, medium-band imaging is free of many of the challenges associated with WFSS observations (such as overlapping source contamination) and can reach greater depths per unit exposure time than WFSS. The medium bands can thus be more efficient for identifying and studying EELGs than more conventional methods.

A simple and effective way of searching for EELGs using medium-band photometry is by using color selections. These color selections target the extreme colors produced by extreme emission lines, which can reach medium-band colors > 2 mag in neighboring filters (e.g., Williams et al. 2023). One advantage of medium-band color selections is that they can select galaxies based on emission-line flux. Unlike the commonly used Lyman break technique, medium-band color selections do not require high signal-to-noise ratios (S/Ns) in the rest-frame UV-optical continuum and can select EELGs that are too faint to be detected through their continuum emission alone. This population of very faint galaxies may play an important role in reionization (e.g., Endsley et al. 2023) yet will not be detected using many of the typical selection criteria. However, faint and low-mass EELGs often have strong emission lines, allowing them to be selected using medium-band color cuts. Additionally, EELGs with red rest-frame UV-optical continuum emission have been shown to mimic the signatures of very high-z Lyman break galaxies selected through their broadband photometry (e.g., Zavala et al. 2023; CEERS-93316 discussed in Arrabal Haro et al. 2023).

We will show that objects such as these can be easily identified using medium-band color selections and can thus be used to identify lower-z contaminants in samples with medium-band imaging.

This work presents a sample of 118 EELGs over 1.7 ≤ z ≤ 6.7. These objects were identified using a set of NIRCam medium-band color cuts that target galaxies with extreme [O III] + Hβ and Hα emission, described in Section 2. We determine the [O III] + Hβ and Hα EWs (Section 3.1) and physical properties (Section 3.2) for the sample and study the evolution of EWs with physical properties of the galaxy and redshift (Section 3.3). Additionally, we present follow-up spectroscopy of 15 of the objects with NIRSpect, which we will use to demonstrate the ability of the medium bands to obtain robust measurements of EW(Hα) and EW([O III] + Hβ) (Section 4). We assume a cosmology of H_0 = 72 km s^{-1} Mpc^{-1}, Ω_m = 0.27, and Ω_λ = 0.73.

2. Observations and Sample Selection

2.1. Observations

This work uses NIRCam imaging obtained as part of the Canadian NIRISS Unbiased Cluster Survey (CANUCS; Willott et al. 2022, Guaranteed Time Observations (GTO) ID 1208). CANUCS observations include deep (~28.9 mag in medium bands and ~29.4 mag in wide bands to 5σ for point sources) NIRCam imaging of flanking fields in five broad (F090W, F115W, F150W, F277W, and F444W) and nine medium-band (F140W, F162M, F182M, F210M, F250M, F300M, F335M, F360M, and F410M) filters. This work uses the first of five CANUCS NIRCam flanking fields near the cluster MACS J0417.5-1154. The data were obtained in a single NIRCam pointing using modules A and B covering an area of 9.7 arcmin². Additionally, ~70% of the flanking field was observed in two Hubble Space Telescope (HST) Wide Field Camera 3/UVIS (WFC3/UVIS) filters (F438W and F606W) to depths of ~28.4 mag at 5σ for point sources (Program ID 16667, PI: M. Bradac). Together, these observations provide a wavelength coverage of λ ~ 0.4–5 μm. Lensing magnification from the cluster is negligible in the flanking field and is thus neglected from this analysis.

The NIRCam data were processed using a combination of the official STScI JWST pipeline (with software version 1.8.0 and CRDS context jwst_1001.pmap) and grizli version 1.6.0 (Brammer & Matharu 2021). The NIRCam and HST data were drizzled onto the same pixel scale of 40 mas pixel^{-1} and registered to Gaia DR3 astrometry. Further details of our processing method are provided in Noirot et al. (2023). Empirical point spread functions (PSFs) were then built from isolated stars in the field, and all images were convolved with kernels to match the PSF of the longest wavelength filter, F444W. These PSF-matched images are used for photometry to ensure colors are not biased by differences in PSF.

2.2. Color Selections

Our sample (see Section 2.3) was selected using a set of color cuts (presented in Table 1) that target galaxies with both extreme [O III] + Hβ and Hα emission. The color cuts were defined by creating synthetic NIRCam observations of SEDs produced by the Yggdrasil stellar population synthesis code (Zackrisson et al. 2011). In order to define our color selections, we selected a subset of the publicly available Yggdrasil SEDs with a Kroupa (2001) initial mass function (IMF); two star formation histories (instantaneous burst and constant), with various ages (0.01–9.1 Myr after star formation began); and metallicities (Z = 0.0004, 0.004, 0.008). The magnitudes in the 16 CANUCS filters were then calculated for each SED redshifted to z = 0.1–15 (with Δz = 0.1 step sizes).
 Additionally, we accounted for the influence of interloper galaxy populations (such as old and dusty galaxies) by creating synthetic observations of SEDs from Flexible Stellar Population Synthesis (FSPS) code (Conroy et al. 2009; Conroy & Gunn 2010). We used this set of synthetic NIRCam observations to search for medium-band color excesses driven by strong [O III] + Hβ emission and Hα emission, which we use to define an initial set of color cuts. We then added photometric scatter to the set of synthetic observations by randomly drawing from a Gaussian distribution assuming various S/Ns (ranging from S/N =2–30). These were then used to evaluate the completeness fractions and contamination when employing various S/N and color cuts (e.g., selections requiring 0.5 mag color versus 1 mag color, targeting galaxies with S/N >2 versus S/N >5). For each set of color and S/N cuts, the completeness fraction was calculated based on the fraction of synthetic galaxies that were selected versus how many would have been selected in the absence of photometric scatter. The impact of contamination from other galaxy populations was assessed in a relative sense, by measuring the amount of contamination when using different sets of color cuts.

With the results of these tests, we define a set of color cuts that select galaxies with extreme [O III] + Hβ and Hα emission over 1.7 ≤ z ≤ 6.7 (Table 1). The tests described above show that our color selections can effectively identify galaxies with EW (Hα) ≥ 500 Å and EW ([O III] + Hβ) ≥ 1000 Å at all redshifts targeted in this work, with completeness fractions >70%. As discussed in Section 1, medium-band color cuts are able to select EELGs based on line flux without the need for strong continuum emission. Nonetheless, we employ an S/N cut of S/N ≥4 in line emission and S/N ≥2 on average in the underlying continuum. We choose to implement this S/N cut since our tests show that it reduces the number of contaminants in our sample; however, this selection will be expanded upon in future work. Additionally, while it is possible to identify EELGs by targeting emission from a single emission-line complex, our color selections require strong emission in both [O III] + Hβ and Hα. Much like the S/N cuts, we choose to do this since our tests show that selecting galaxies on two emission lines provides a more reliable estimate of galaxy redshift than with one line.

The animation in Figure 1 illustrates the color cuts used in this work, in which the colors of five neighboring medium bands are used to target galaxies over 3.5 ≤ z ≤ 5.5, demonstrating the extreme colors created by the Hα and [O III] + Hβ lines. Overall, our selection criteria consists of ten color cuts that were chosen based on how effective they were at selecting EELGs at the correct redshifts. These ten color cuts are presented in Table 1, which shows the color cut (Col. 1), the redshifts they probe (Col. 2), filters containing the Hα and [O III] + Hβ emission lines (Col. 3), and the filters used to estimate the continuum emission (Col. 4). Each set of color cuts has at least two criteria, one that targets extreme [O III] + Hβ emission and one that targets extreme Hα emission.

### Table 1

<table>
<thead>
<tr>
<th>Color Cut Col. 1</th>
<th>Redshifts Selected Col. 2</th>
<th>Emission-line Filters Col. 3</th>
<th>Continuum Filters Col. 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>F410M – F444W &gt; 0.5</td>
<td>z = 5.8–6.7</td>
<td>Hα: F444W</td>
<td>F140M, F162M, F182M,</td>
</tr>
<tr>
<td>F410M – F444W &gt; 0.5</td>
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<td>Hα: F444W</td>
<td>F140M, F162M, F182M,</td>
</tr>
<tr>
<td>F360M – F410M &gt; 0.5</td>
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<td>Hα: F410M</td>
<td>F140M, F162M, F182M,</td>
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<tr>
<td>F360M – F410M &gt; 0.5</td>
<td>z = 4.8–5.5</td>
<td>Hα: F410M</td>
<td>F155W, F162M, F182M,</td>
</tr>
<tr>
<td>F300M – F335M &lt; −1</td>
<td>(…),</td>
<td>[O III] + Hβ: F300M</td>
<td>F360M</td>
</tr>
<tr>
<td>F360M – F410M &lt; −0.5</td>
<td>z = 4.2–4.4</td>
<td>Hα: F335M</td>
<td>F155W, F162M, F182M,</td>
</tr>
<tr>
<td>F250M – F300M &lt; −1</td>
<td>(…),</td>
<td>[O III] + Hβ: F250M</td>
<td>F410M</td>
</tr>
<tr>
<td>F300M – F335M &gt; 0.5</td>
<td>z = 3.8–4.2</td>
<td>Hα: F335M</td>
<td>F155W, F162M, F182M,</td>
</tr>
<tr>
<td>F335M – F360M &lt; −0.5</td>
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<td>[O III] + Hβ: F250M</td>
<td>F300M, F410M</td>
</tr>
<tr>
<td>F250M – F300M &gt; 0.5</td>
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<td>Hα: F300M</td>
<td>F900W, F115W, F140M,</td>
</tr>
<tr>
<td>F182M – F210M &gt; 0.5</td>
<td>z = 2.7–2.9</td>
<td>Hα: F210M</td>
<td>F900W, F115W, F300M,</td>
</tr>
<tr>
<td>F182M – F210M &gt; 0.5</td>
<td>z = 2.1–2.3</td>
<td>Hα: F210M</td>
<td>F900W, F182M, F250M,</td>
</tr>
<tr>
<td>F140M – F162M &lt; −1</td>
<td>z = 1.7–2</td>
<td>Hα: F182M</td>
<td>F900W, F162M, F210M,</td>
</tr>
</tbody>
</table>

Note: The table includes the color cuts (Col. 1), the redshifts they probe (Col. 2), filters containing the Hα and [O III] + Hβ emission lines (Col. 3), and the filters used to estimate the continuum emission (Col. 4). Each set of color cuts has at least two criteria, one that targets extreme [O III] + Hβ emission and one that targets extreme Hα emission.
2.3. Sample

Based on the color and S/N cuts described in Section 2.2, we select 118 objects over $1.7 \leq z \leq 6.7$ with extreme [O III] + Hβ and Hα emission. As noted in Section 1, color cuts similar to those used in this work can select galaxies based on emission-line EW, with no dependence on strong rest-frame UV-optical continuum. This is advantageous to more typically used selections for high-$z$ galaxies since it is able to target galaxies with faint or red continuum fluxes for which a Lyman break cannot be observed. This is exemplified in Figure 2, which shows three examples of EELGs found using the medium-band color selections. All three examples show flux excesses in two filters driven by strong [O III] + Hβ and Hα emission. Two of the examples (ID 1203427 and 1204847) exhibit blue continuum slopes and show clear evidence of a Lyman break. However, the third example (ID 1205006) has a very red continuum, which results in an absence of a Lyman break. Objects such as these are similar to CEERS-93316 (Arrabal Haro et al. 2023), which have been shown to contaminate samples of photometrically selected very high-$z$
galaxies (see also Zavala et al. 2023). The ability of medium-band color cuts to select galaxies such as these can provide a powerful tool in the search for very high-$z$ galaxies by identifying lower-$z$ interlopers in those samples.

3. Analysis

3.1. Rest-frame Equivalent Widths

Rest-frame EW([O III] + Hβ) and EW(Hα) were calculated directly from the photometry by fitting the continuum flux to a power law, $f_\nu \propto \lambda^{\alpha}$. Different continuum filters were used for each of the ten selection criteria and were chosen by avoiding filters that may be contaminated with emission lines (such as [O II] or Paβ) at the galaxy redshift. Photometric redshifts were determined using EAZY (Brammer et al. 2008), with templates from FSPS (Conroy et al. 2009; Conroy & Gunn 2010) and Larson et al. (2022) by limiting the allowed best-fit redshifts to those implied by the color selections. This allowed us to obtain a precise redshift for each galaxy that is consistent with the findings of the color selections. Additionally, we ran EAZY over an expanded redshift range of $0 < z < 20$. Only three objects have different photometric redshifts when EAZY is run.
over the expanded and restricted ranges, and these have been excluded from our sample. The EWs calculated this way will be overestimated since the contribution from weaker emission lines (such as [N II] for Hα and the Balmer lines for [O III] + Hβ) was not removed prior to calculations. However, it is not expected that these lines will contribute significantly to the EW compared to the much stronger [O III] + Hβ and Hα emission lines (e.g., Izotov et al. 2019; Cameron et al. 2023). The filters used to measure the line fluxes and continuum emission are listed along with the selection criteria in Table 1.

Figure 3 shows the distribution of EW([O III] + Hβ) and EW(Hα) for the entire sample (top panel) and with the sample separated into four redshift bins (bottom panels). This figure demonstrates that very high EW systems do exist over $1.7 \lesssim z \lesssim 6.7$, with EW >1000 Å in both [O III] + Hβ and Hα, sometimes even reaching EW ~3000 Å. Other searches for EELGs have revealed similarly high EW objects (e.g., Robertson et al. 2015; Smit et al. 2015; Endsley et al. 2021; Stefanon et al. 2022; Rinaldi et al. 2023 at high z; Reddy et al. 2018; Onodera et al. 2020; Boyett et al. 2022 at intermediate z); however, the most extreme objects are quite rare and represent only a small sample of the total star-forming galaxies at any given redshift.

3.2. Physical Properties

The Dense Basis (Iyer et al. 2019) SED-fitting code was used to compute the physical properties of EELGs in the sample. Fitting was performed using Kron aperture photometry, assuming the Calzetti (2001) dust law and Kroupa (2001) IMF, and at the best-fit redshift from EAZY (see Section 3.1). Additionally, Dense Basis was allowed stellar masses of $7 < \log(M_*/M_\odot) < 12$, dust attenuation of $0 < A_V < 4$, and metallicities of $-2 < \log(Z/Z_\odot) < 0.3$, (using flat priors for all properties). The Dense Basis fitting shows that galaxies in our sample are typically low mass ($7.34 \lesssim \log(M_*/M_\odot) \lesssim 9.47$, with median $\log(M_*/M_\odot) = 8.02$), low metallicity (0.058 ≤ Z/Z_0 ≤ 0.30 with median $Z = 0.14Z_\odot$), with little dust attenuation (0.016 mag ≤ A_V ≤ 0.63 mag with median A_V = 0.18 mag), and high SSFR ($7.66 \times 10^{-10}$ yr^{-1} ≤ SSFR ≤ $4.35 \times 10^{-8}$ yr^{-1} with median SSFR = $1.18 \times 10^{-8}$ yr^{-1}). Furthermore, a visual inspection of the images reveals most of the EELGs are compact with little to no structure. However, there is a small number of EELGs that show evidence of interactions or mergers, such as example 1 (ID 1203427) of Figure 2. Other works on EELGs find similar properties, at both high z (e.g., Asada et al. 2023; Sun et al. 2023) and intermediate z (e.g., Tang et al. 2019).

3.3. Dependence of Equivalent Widths on Physical Properties and Redshift

Figure 4 shows the dependence of rest-frame [O III] + Hβ and Hα EWs with stellar mass (left) and redshift (right), including the median values for galaxies with $7.9 < \log(M_*/M_\odot) < 8.5$ (a mass range that is covered in each of the redshift bins used in Figure 3). The left and right panels of Figure 4 illustrate several important points about our sample of EELGs. First, a visual inspection of the left panel of Figure 4 shows that our sample reproduces the known anticorrelation between rest-frame EW(Hα) and stellar mass (e.g., Onodera et al. 2020; Matthee et al. 2023; Rinaldi et al. 2023). However, there does not appear to be any correlation between rest-frame EW([O III] + Hβ) and stellar mass. To test this, we performed the Spearman’s rank-order correlation test on the distributions. The tests yield $r_{150} = -0.18$, $p_{150} = 0.045$, and $r_{150}^f_{\text{inj} + H\beta} = -0.0033$, $p_{150}^f_{\text{inj} + H\beta} = 0.97$, confirming that there exists an anticorrelation between EW(Hα) and stellar mass, and no correlation of EW([O III] + Hβ) and stellar mass. Taken at face value, this trend of constant EW([O III] + Hβ) with stellar mass indicates that metallicity of the EELGs may remain roughly constant with stellar mass over $7.34 \lesssim \log(M_*/M_\odot) \lesssim 9.47$. However, this conclusion is only tentative given that our sample contains selection biases for the strongest EWs and therefore may be incomplete at lower EWs.

Additionally, the right panel of Figure 4 shows evidence of increasing EW([O III] + Hβ) and EW(Hα) with redshift, a trend that is also observed in Figure 3. The same behavior has been observed in other populations of EELGs (e.g., Reddy et al. 2018; Matthee et al. 2023) and is generally attributed to higher SSFRs at earlier times (e.g., Reddy et al. 2018).

4. Robustness of Estimating Equivalent Widths with the Medium Bands

We obtained follow-up spectroscopy for 15 of the objects presented in this paper, acquired with NIRSpec in multi-object spectroscopy mode using ~3 ks integration times. Spectra were taken using the prism, which provides low-resolution spectroscopy ($R \sim 100$) over $\lambda \sim 0.6$–5.3 μm. The spectroscopy processing was performed with a combination of the official STScI JWST pipeline (with software version 1.8.4 and CRDS context jwst_1030.pmap) and the msaexp package (Brammer 2022). Level 1 processing of raw data into count-rate files used the standard pipeline with the jump step option expand_large_events enabled to mitigate snowball residuals and a custom persistence correction that masks pixels that approach saturation for any readout groups within the subsequent 1200 s, based on an analysis of the typical NIRSpec detector persistence timescale. Level 2 processing performed the standard wavelength, flat-field, path-loss correction and photometric calibration steps. Individual 2D spectra were combined, and optimal 1D extractions (Horne 1986) were done using msaexp.

Figure 5 show two examples of our spectra, which correspond to the first (ID 1203427, top panel) and third (ID 1205006, bottom panel) examples in Figure 2. In all cases, the spectra confirm that these objects are EELGs. They each have strong Hα and [O III] + Hβ emission as well as some weaker lines including Lyα, [O II], and the Balmer lines. Additionally, the top panel of Figure 6 shows the photometric redshifts versus spectroscopic redshifts for all 15 objects with follow-up spectroscopy. This plot demonstrates a remarkably good agreement between the photometric and spectroscopic redshifts, with $|z_{\text{phot}} - z_{\text{spec}}|/(1 + z) = 0.0087$, and illustrates the effectiveness of the medium bands at selecting EELGs over $1.7 \lesssim z \lesssim 6.7$.

Finally, the middle and bottom panels of Figure 6 plot the EW(Hα) and EW([O III] + Hβ) measured from photometry versus spectroscopy. The spectroscopic EWs were calculated by fitting the continuum surrounding the emission lines with a straight line, which was then used to estimate the underlying continuum emission. The continuum fluxes need to be accurately measured in order to calculate EWs, which requires sufficient S/N in the continuum. While the Hα and [O III] + Hβ emission lines are well detected in all 15 spectra,
Figure 3. Histograms showing EW([O III] + Hβ) (purple) and EW(Hα) (blue) for the entire sample (top panel) and as a function of redshift (bottom four panels). Each panel also shows the median EW([O III] + Hβ) (gray dashed line) and median EW(Hα) (gray dashed–dotted line). This figure demonstrates that very strong EELGs do exist over z ∼ 1.7–6.7, reaching EW > 1000 Å, and that the median EW(Hα) and EW([O III] + Hβ) increases with redshift.
Figure 4. Left: EW([O III] + Hβ) (purple) and EW(Hα) (blue) as a function of stellar mass, with a line of best fit for EW([O III] + Hβ) (dashed line) and EW(Hα) (dashed–dotted line). The median EWs for galaxies with 7.9 < log(M_*/M⊙) < 8.5 are plotted as blue (Hα) and purple ([O III] + Hβ) stars. Galaxies in this sample reproduce the known anticorrelation between EW(Hα) and stellar mass but show no evolution of EW([O III] + Hβ) and stellar mass. Right: EW([O III] + Hβ) (purple) and EW(Hα) (blue) as a function of redshift. Also plotted are the median EWs for galaxies in the same four redshift bins as Figure 3 with 7.9 < log(M_*/M⊙) < 8.5 as the blue (Hα) and purple ([O III] + Hβ) stars. This panel shows how the EWs of galaxies in our sample increases with redshift, which is likely driven by increasing SSFRs at earlier times.

Figure 5. Examples of the NIRSpec spectra of two EELGs in the sample. The top panel corresponds to the first example in Figure 2 (ID 1203427), and the bottom panel corresponds to the third example in Figure 2 (ID 1205006). Various optical emission lines are labeled on the spectra, in purple if they are detected and in blue if they are not. Strong Hα and [O III] + Hβ emission is observed in both spectra, confirming that the color cuts are able to accurately select EELGs.
several galaxies had continua that were too faint to reliably calculate EWs and were thus excluded from this analysis. Additionally, we were unable to measure the $\text{[O III]} + \text{H}\beta$ lines for two galaxies since that portion of the spectrum fell in the NIRSpec detector gaps. In total, EW(H$\alpha$) was calculated for ten spectra, and EW($\text{[O III]} + \text{H}\beta$) was calculated for thirteen.

The two bottom panels of Figure 6 show a general agreement between EWs calculated from medium-band photometry and from the spectra and confirm the existence of very high EWs.

**Figure 6.** Comparison of redshifts (top), EW(H$\alpha$) (middle), and EW($\text{[O III]} + \text{H}\beta$) (bottom) measured from the NIRSpec spectra vs. the medium-band photometry. There is a remarkable agreement between the spectroscopic and photometric redshifts, with mean $|z_{\text{phot}} - z_{\text{spec}}|/(1 + z) = 0.0087$. Spectroscopic redshifts measured directly from the automated pipeline are shown as purple diamonds. The automated pipeline incorrectly measured the redshift for one object, and the correct spectroscopic redshift is plotted as a green star. The EWs measured from the spectra and photometry do generally agree with each other; however, the agreement is better for EW(H$\alpha$) than for EW($\text{[O III]} + \text{H}\beta$). These differences are likely driven by uncertainties in continuum estimates when calculating EWs from the medium-band photometry and when emission lines are not fully contained in the filter used to estimate the line flux. This is observed in two of our spectra, which are indicated by a light outline (corrected EW calculated using a wide band instead of medium band) and dark outline (not corrected).
systems with EW([O III] + Hβ) ~3000 Å. While the EWs calculated from medium-band photometry and spectroscopy do generally agree, the agreement is not perfect and is worse for EW([O III] + Hβ). There are likely two sources of error that drive this disagreement. First is uncertainties in estimating the continuum emission when calculating EWs using medium-band photometry since certain areas of the spectrum are contaminated by the presence of other strong emission lines. This causes the continuum to be poorly constrained in those regions and results in incorrect EW measurements, particularly for lower-z galaxies. While care was taken to avoid strong emission lines when estimating the continuum, certain regions of the spectrum are heavily contaminated, which makes it challenging to obtain clean measurements of the continuum. This is particularly true for the blue side of the [O III] + Hβ line complex, which is populated by [O II] and Balmer line emission.

Second, the EWs were calculated assuming all of the flux from a given emission-line complex falls in one filter. However, this assumption does not always hold true and can lead to EWs being underestimated when calculated from medium-band photometry. This phenomenon is observed in two of our spectra, including one object that had a >1000 Å difference in spectroscopic and photometric EW([O III] + Hβ). For this object, we recalculate its EW([O III] + Hβ) using an overlapping wide band to estimate the line flux, instead of the medium band originally used. The wide band fully contains the [O III] + Hβ emission lines and yields an EW that is more in line with that measured from its spectrum. The EW calculated in this way is shown in Figure 5, plotted with the light outline. The second object that has emission lines ([O III] + Hβ lines) spread across multiple filters does not overlap with a wide band filter, and its EW was not recalculated. This object is plotted with a dark outline in Figure 5, and the photometric EW is likely underestimated due to missing line flux in the filter used to measure the EW. Based on inspection of the photometric and spectroscopic redshifts, we estimate that ~7%–15% of galaxies in our sample may suffer from this issue.

The discrepancies in EWs measured from spectroscopy and photometry demonstrate that a more detailed method is required to accurately calculate EWs from medium-band photometry. However, given the simple methods used to measure EWs in this work, our present analysis reveals a remarkable agreement between EWs measured using photometry and spectroscopy. A more detailed calculation of EWs from medium-band photometry appears to be a quite complex issue and will be fully addressed in a future work. This will involve more care to the filter throughput curves when calculating EWs, developing an algorithm capable of identifying and measuring EWs when emission lines are not fully contained in a single filter, and improving continuum measurements (e.g., using SED fits to measure the continuum).

5. Conclusion

This Letter presents an analysis of 118 extreme Hα and [O III] + Hβ emitters over 1.6 ≤ z ≤ 6.7 selected from NIRCam observations as part of the CANUCS GTO program. These sources were identified using a set of medium-band color cuts and include some very red galaxies (see the third example, ID 1205006, in Figure 2), which have continuum fluxes rewards of the Lyman break (λrest > 1216 Å) that are too faint to be detected. Objects such as these demonstrate the ability of our color cuts to select galaxies on emission-line flux, with no dependence on continuum flux. Thus, we show medium-band color selections are a powerful tool that can identify very faint galaxies that may play an important role in reionization and objects that contaminate photometrically selected samples of very high-z galaxies.

We calculate the EWs (Section 3.1) and physical properties (Section 3.2) of the EELGs in our sample. They all have very high [O III] + Hβ and Hα EWs, sometimes up to ~3000 Å. Their physical properties are typical of EELGs: low mass, low metallicity, high SSFRs, and compact morphologies. Additionally, we show that the EELGs in our sample follow trends of increasing EW(Hα) and EW([O III] + Hβ) with redshift, an anticorrelation between EW(Hα) and stellar mass, and no correlation between EW([O III] + Hβ) and stellar mass (Sections 3.1, 3.3; Figures 3, 4). Finally, we present follow-up NIRSpec spectroscopy of 15 of these sources (Section 4). These spectra confirm that medium-band color cuts are able to efficiently select EELGs over a wide range of redshifts and can be used to measure EWs remarkably well given the simple methods used in this work (Figures 5, 6). That said, we do note the need for a more detailed method of calculating EWs from the photometry as significant discrepancies between EWs measured from photometry and spectroscopy do exist for [O III] + Hβ.

It is important to reiterate that the color selections used in this work target the brightest and most extreme EELGs with strong Hα and [O III] + Hβ emission in the first of five CANUCS fields. This leaves open many avenues for future work that will allow us to significantly expand the sample of galaxies presented and discussed in this Letter. These include searches for fainter and less extreme EELGs, color selections involving only one emission-line complex, incorporation of full photometric redshift fitting with appropriate templates, and analysis of the remaining four CANUCS NIRCam flanking fields.

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Data Availability

The JWST data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST) at the Space Telescope Science Institute. The data will be available following the end of the 1 yr exclusive access period at doi:10.17909/ph4n-6n76.

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