



The Physical Origin of Extreme Emission Line Galaxies at High Redshifts: Strong [O III] Emission Lines Produced by Obscured Active Galactic Nuclei

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Abstract

We present deep Subaru/FOCAS spectra for two extreme emission line galaxies (EELGs) at $z \sim 1$ with strong [O III] $\lambda 5007$ emission lines, exhibiting equivalent widths (EWs) of 2905^{+946}_{-578} Å and 2000^{+188}_{-159} Å, comparable to those of EELGs at high redshifts that are now routinely identified with JWST spectroscopy. Adding a similarly large [O III] EW (2508^{+1487}_{-689} Å) EELG found at $z \sim 2$ in the JWST CEERS survey to our sample, we explore the physical origins of the large [O III] EWs of these three galaxies with the Subaru spectra and various public data including JWST/NIRSpec, NIRCам, and MIRI data. While there are no clear signatures of active galactic nuclei (AGNs) identified by the optical line diagnostics, we find that two out of two galaxies covered by the MIRI data show strong near-infrared excess in the spectral energy distributions (SEDs), indicating obscured AGNs. Because none of the three galaxies show clear broad H β lines, the upper limits on the flux ratios of broad H β to [O III] lines are small, $\lesssim 0.15$ that are comparable with Seyfert 1.8–2.0 galaxies. We conduct CLOUDY modeling with the stellar and AGN incident spectra, allowing a wide range of parameters, including metallicities and ionization parameters. We find that the large [O III] EWs are not self-consistently reproduced by the spectra of stars or unobscured AGNs, but obscured AGNs that efficiently produce O⁺⁺ ionizing photons with weak nuclear and stellar continua that are consistent with the SED shapes.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); Emission line galaxies (459)

1. Introduction

Nebular spectra can provide information on understanding galaxies' properties. Emission lines can be used as a probe to trace the incident UV radiation (e.g., M. S. Oey et al. 2000; L. J. Kewley et al. 2019; Y. Isobe et al. 2022). Particularly, the forbidden lines [O III] $\lambda\lambda 4959, 5007$ ([O III] doublets) play a pivotal role. The high excitation lines are often driven by ionizing photons produced in massive and short-lived O and B stars or active galactic nuclei (AGNs), whereas they are

surrounded by the rest-optical continuum mainly contributed by less massive and longer-lived stars.

Extreme emission line galaxies (EELGs) are characterized by their notably strong emission lines in comparison to their stellar continuum, resulting in unusually high emission line equivalent widths (EWs). Over the last decade, EELGs have been studied in detail at very low redshift, especially those galaxies identified by their extremely large EWs of [O III] $\lambda 5007$ ([O III] emitters; e.g., the “green pea” population (C. Cardamone et al. 2009; Y. I. Izotov et al. 2011; A. E. Jaskot & M. S. Oey 2013) and the “blueberry” population (H. Yang et al. 2017)). The typical [O III] EW is 20 Å in the Sloan Digital Sky Survey (SDSS; e.g., S. Alam et al. 2015), and only <1% of SDSS galaxies exhibit [O III] EWs $\gtrsim 1000$ Å. Most EELGs are considered to be



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undergoing strong star formation (Y. I. Izotov et al. 2011; K. N. K. Boyett et al. 2022). In comparison, several studies (e.g., A. Baskin & A. Laor 2005; A. Caccianiga & P. Severgnini 2011; J. R. Mullaney et al. 2013) show that the narrow-line EWs of AGNs can also have a large value of $\text{EW}([\text{O III}]) \sim 2000 \text{ \AA}$, suggesting that not all EELGs should be simply attributed to star-forming galaxies.

The launch of the James Webb Space Telescope provides abundant unprecedented data in terms of both spectra and images (J. Rigby et al. 2023). It enables sensitive near-infrared spectroscopy out to $5.2 \mu\text{m}$ with NIRSpec (P. Jakobsen et al. 2022), permitting direct measurement of the EWs of $[\text{O III}] \lambda 5007$ out to high redshift ($z < 9.5$). Recent research indicates that, in the early Universe, EELGs were significantly more abundant (e.g., J. Matthee et al. 2023; F. Sun et al. 2023; K. Boyett et al. 2024; M. W. Topping et al. 2024). Plus, the MIRI (G. S. Wright et al. 2023) on JWST provides nine photometric bands from 5 to $26 \mu\text{m}$, which are about 10–100 times more sensitive than the Spitzer mission. It allows us to further inspect the mid-infrared properties of low- z galaxies, such as the hot dust emission.

The physical origins of EELGs determined by optical line diagnostics remain more uncertain than expected. According to the diagnostics of the Baldwin, Phillips, and Terlevich (BPT; J. A. Baldwin et al. 1981) diagram, most EELGs are considered to be undergoing strong star-forming activities, while a small fraction are AGNs (e.g., the “Galaxy Zoo” AGN fraction is 17%; C. Cardamone et al. 2009). It is noteworthy that recent reports suggest that low-metallicity AGNs with $Z < Z_{\odot}$ are located in the same region as star-forming galaxies in the classical BPT diagram (e.g., Y. I. Izotov & T. X. Thuan 2008; Y. Harikane et al. 2023; R. Maiolino et al. 2024; J. Chisholm et al. 2024; Y. Yao et al. 2024). In fact, the majority of local EELGs feature low metallicity ($Z \lesssim 0.2Z_{\odot}$; K. N. K. Boyett et al. 2022), indicating that the BPT diagram is not sufficient to determine the physical origins of low-metallicity EELGs.

Particularly, in the Subaru High- z Exploration of Low-luminosity Quasars (SHELLQs) survey, Y. Matsuoka et al. (2018) spectroscopically identified several $[\text{O III}]$ emitters at $z \sim 0.8$. Notably, two of these emitters are reported to have unprecedentedly large EWs of $[\text{O III}]$, exceeding $4000 \text{ \AA}$. However, such high EWs of $[\text{O III}] \lambda 5007$ are difficult to explain with classic stellar population models that typically predict lower EWs ($\lesssim 3000 \text{ \AA}$; A. K. Inoue 2011). Therefore, we conducted deeper follow-up observations, aiming to examine the previous measurement and uncover the underlying mechanisms driving these extraordinary emission characteristics. Furthermore, we search for similarly extreme EW objects in the JWST programs.

This paper is structured as follows. Section 2 provides details of the new observation and the JWST data set we use. We outline basic information about objects, data reduction, and selection criteria. Section 3 presents the basic physical properties implied by the spectroscopic and photometric measurement. Section 4 discusses the physical origins of $[\text{O III}]$ emitters and implications for our findings. Throughout this paper, we assume the standard ΛCDM model with the cosmological parameters from Planck 2018 (Planck Collaboration et al. 2020): $\Omega_m = 0.3111$, $\Omega_{\Lambda} = 0.6899$, $\Omega_b = 0.0489$, $h = 0.6766$, and $\sigma_8 = 0.8102$. We measure the EWs in the rest frame. We adopt the solar abundance from M. Asplund et al. (2009; $Z_{\odot} = 0.014$).

Table 1
Source Information for Our $[\text{O III}]$ Emitters

ID	R.A.	Decl.	Redshift	t_{exp}^a (hr)
J1000+0211	10:00:12.46	+02:11:27.4	0.828	4.33
J0845–0123	08:45:16.54	–01:23:21.6	0.728	3.67
CEERS-3506	14:20:37.51	+53:03:35.6	2.055	1.70

Note.

^a The total exposure time of the spectra used in this work, which covers the $[\text{O III}] \lambda 5007$ emission line.

2. Sample and Data

2.1. Subaru

2.1.1. Subaru Sample

We select the two most extreme sources from the SHELLQs survey (Y. Matsuoka et al. 2018). Their basic properties are summarized in Table 1.

2.1.2. Subaru Observations

We conducted new spectroscopic observations with the Faint Object Camera and Spectrograph (FOCAS; N. Kashikawa et al. 2002) on the Subaru Telescope. These observations took place over two consecutive nights, 2020 December 24–25, during the S20B semester (proposal ID: S20B0002N; PI: Y. Harikane). We operated FOCAS in its multiobject spectroscopy mode, employing the VPH850 grism in conjunction with the SO58 order-cut filter. This setup covered a wavelength range of $5800\text{--}10000 \text{ \AA}$. The slit width was set to $0''.8$, which yielded a spectral resolution of $R \sim 1500$. Integration times were set to 3.67 and 4.33 hr for J0845–0123 and J1000+0211, respectively, which are significantly longer than those of the FOCAS observations in Y. Matsuoka et al. (2018; ~ 10 minutes for each object), who first identified these objects. We also utilized the VPH650 grism to obtain the spectra in the observed wavelength range of $5300\text{--}7700 \text{ \AA}$, to cover the $[\text{O II}] \lambda \lambda 3727$, 29 doublet emission lines with a resolution of $R \sim 2500$. The total integrated exposure time of observations with VPH650 is 20 minutes for each object.

2.1.3. Subaru Data Reduction

In this section, we detail the reduction process of the Subaru data. Utilizing the Image Reduction and Analysis Facility along with the FOCASRED package from the official FOCAS website, we carry out a series of standard data reduction procedures, including bias and overscan subtraction, flat-fielding corrections, and background subtraction. We conduct wavelength calibration by identifying sky emission lines. Flux calibration is achieved with the standard star Feige 34. We make error spectra consisting of Poisson photon noise and readout noise that is estimated with the CCD overscan regions. Figure 1 displays the 2D and 1D spectra featuring the strong $\text{H}\beta + [\text{O III}]$ doublets in the rest frame.

2.2. Keck

We observed J1000+0211 and J0845–0123 with the Multi-Object Spectrometer for Infra-Red Exploration (MOSFIRE) on the Keck I telescope on 2020 January 20 (proposal ID:

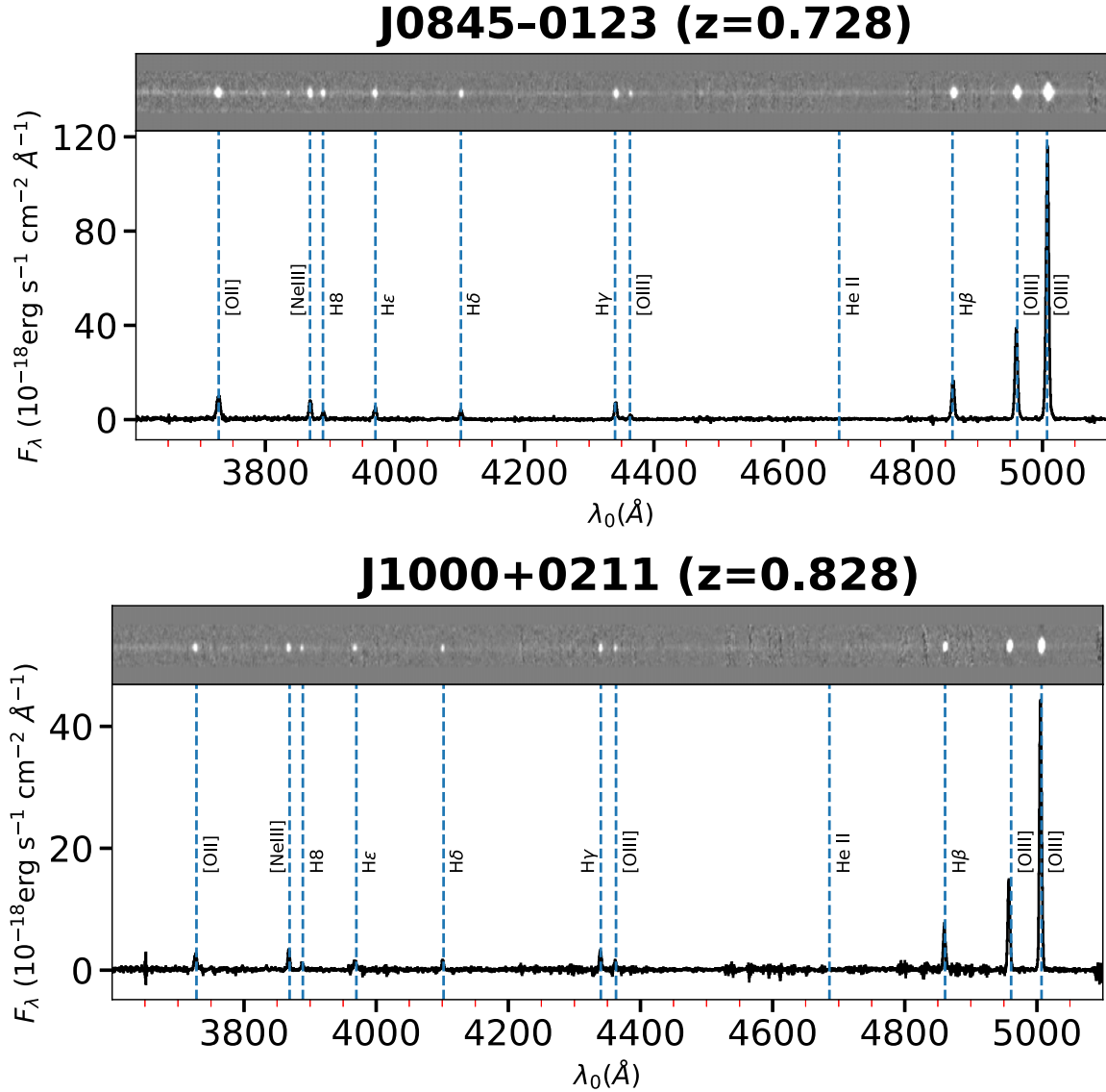


Figure 1. Rest-frame 1D and 2D spectra of J0845–0123 (top) and J1000+0211 (bottom). They exhibit several emission lines, including the strong H β + [O III] doublet emission lines. A faint continuum is detected.

S19B0052; PI: Y. Harikane). The spectra are taken with the *J* band covering 1.15–1.35 μm , targeting the H α , [N II] $\lambda 6484$, and [S II] $\lambda \lambda 6717$, 37 lines redshifted to $z \sim 0.8$. The total integration time is 50 minutes for each object. The average seeing size is $\sim 0''.6 - 0''.9$ for both J1000+0211 and J0845–0123. The slit width is $0''.7$, leading to a spectral resolution of $R \sim 3318$.

The data are reduced by using the MOSFIRE data reduction pipeline.²¹ This pipeline performs flat-fielding corrections, wavelength calibration, sky subtraction, and cosmic ray removal. After combining the spectra, we detect the H α line in J1000+0211, while the H α line of J0845–0123 is in the wavelength gap.

2.3. JWST

We extensively attempt to search for sources similar to Subaru emitters in the publicly available JWST data sets.

2.3.1. JWST Sample

The Cosmic Evolution Early Release Science (CEERS; ERS 1345; PI: S. Finkelstein; M. B. Bagley et al. 2023; S. L. Finkelstein et al. 2023) data were taken with the JWST/NIRSpec prism covering 0.6–5.3 μm as well as the medium-resolution filter-grating pairs of F100LP-G140M, F170LP-G235M, and F290LP-G395M covering the wavelength ranges of 1.0–1.6, 1.7–3.1, and 2.9–5.1 μm , respectively.

In our work, we use the data reduced by Grizli (G. Brammer 2023a), and they are made available through the Cosmic Dawn Center. These data can be retrieved from the DAWN JWST Archive (DJA).²² Details of the reduction of the DJA data are presented in G. Brammer (2023b), K. E. Heintz et al. (2024), and F. Valentino et al. (2023). We utilized the spectroscopic redshifts from the DJA catalog to derive the rest-frame spectra for each source.

We use the method for EW measurements detailed in Section 3.1. Suppose the continuum is so faint that the 16th

²¹ <http://code.google.com/p/mosfire>

²² <https://dawn-cph.github.io/dja/>

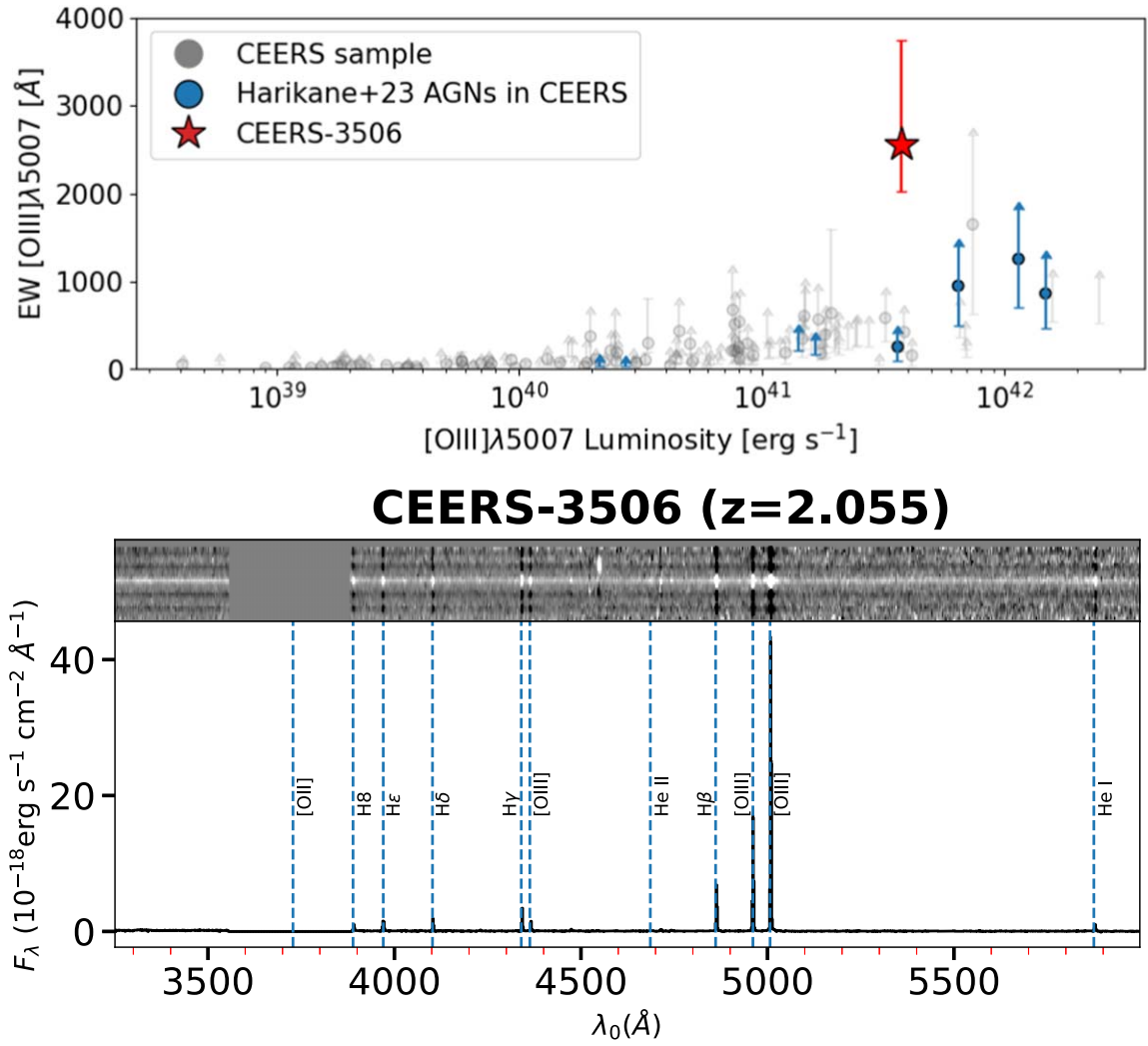


Figure 2. Top panel: [O III] $\lambda 5007$ EW vs. luminosity distribution of our CEERS sample. CEERS-3506 is highlighted as the red star, while other objects are in gray. The blue markers are AGNs reported in Y. Harikane et al. (2023). The arrows denote 1σ lower limits for sources whose 16th percentile of the estimated probability distribution of the continuum is lower than 0. For each object, the circle marks the median of the EW value; however, if the median is less than 0 due to nondetection of a faint continuum, only the 1σ lower limit is shown. Bottom panel: the 2D and 1D spectra of CEERS-3506, which include the $H\beta + [O III]$ emission lines, in the same manner as Figure 1.

and/or 50th percentiles of the estimated probability distribution of the continuum are lower than zero. In that case, we can only establish an upper limit on the continuum and, consequently, a lower limit on the EW. Our sample is restricted to sources with at least one medium-resolution spectrum covering the wavelength range of 4800–5200 Å, and the [O III] $\lambda 5007$ line is not in the instrument gap. Out of 153 sources, one galaxy is identified with extremely high EW([O III] $\lambda 5007$) similar to our Subaru EELGs, exhibiting a 1σ lower limit exceeding 1000 Å. This finding is presented in Figure 2. The basic information of the CEERS EELG is also shown in Table 1.

2.3.2. JWST Spectrum

The NIRSpec spectroscopy of this source has an ID from the microshutter array of 3506; thus we refer to it as CEERS-3506 hereafter. [O III] $\lambda 5007$ falls within the range of the filter-grating pair F100LP-G140M. Figure 2 exhibits the 2D and 1D spectra of this specific filter-grating pair that features strong $H\beta + [O III]$ doublet emissions. In addition, the $H\alpha$ line is captured by the F170LP-G235M spectrum. The F290LP-G395M spectrum encompasses both $Pa\beta$ and He I 10830. However,

the [O II] $\lambda\lambda 3727, 3729$ doublets lie within an instrument gap of the F100LP-G140M spectrum.

2.4. Photometric Data

For J1000+0211, our data set includes images from the Subaru Hyper Suprime-Cam (HSC; H. Aihara et al. 2018) in the g, r, i, z , and y bands, acquired as part of the third data release of the HSC-SSP survey (H. Aihara et al. 2022). Additionally, we utilize JWST NIRcam images in the F090W, F115W, F150W, F200W, F277W, and F444W bands, and JWST MIRI images in the F770W and F1800W bands, sourced from both the COSMOS-Web (GO 1727; PI: J. Kartaltepe; C. M. Casey et al. 2023) and PRIMER (GO 1837; PI: J. S. Dunlop; J. S. Dunlop et al. 2021) programs. For CEERS-3506, our data comprise HST ACS images in the F435W, F606W, and F814W bands, HST WFC3 images in the F125W and F160W bands from the CANDLE survey (N. A. Grogin et al. 2011; A. M. Koekemoer et al. 2011) and JWST MIRI images in the F770W, F1000W, F1280W, F1800W, and F2100W bands from the CEERS survey. For J0845–0123, our data are limited to the Subaru-HSC images.

Table 2
Selected Observed Emission-line Fluxes and EWs of Our [O III] Emitters

ID	[O II] $\lambda\lambda 3727, 29$	H γ	[O III] $\lambda 4363$	H β	[O III] $\lambda 4959$	[O III] $\lambda 5007$	H α	[N II] $\lambda 6484$	[S II] $\lambda 6717$	[S II] $\lambda 6731$	[O II] $\lambda 7320$	[O II] $\lambda 7330$	[S III] $\lambda 9531$	Flux(H β) ($10^{-18}\text{erg s}^{-1}\text{cm}^{-2}$)	EW([O II] $\lambda\lambda 3727, 29$) ($\text{\AA}$)	EW ([O III] $\lambda 4959$) ($\text{\AA}$)	EW ([O III] $\lambda 5007$) ^a ($\text{\AA}$)	EW (H β) ($\text{\AA}$)	EW(H α) ($\text{\AA}$)	EW([O III] $\lambda\lambda 4959, 5007$ +H β) ($\text{\AA}$)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)
CEERS-3506	...	45.3 ± 1.6	23.5 ± 1.0	100 ± 2.4	253 ± 11	651 ± 27	282 ± 10	<0.69	1.36 ± 0.47	2.23 ± 0.56	0.71 ± 0.46	0.42 ± 0.35	5.91 ± 0.55	22.1 $\pm$ 0.5	...	984 ⁺⁵⁷⁴ ₋₂₇₄	2508 ⁺¹⁴⁸⁷ ₋₆₈₉	341 ⁺¹³³ ₋₇₂	1618 ⁺⁵²⁶ ₋₃₇₈	3868 ⁺²²⁹² ₋₁₀₆₄
J1000+0211	51.0 ± 7.5	45.2 ± 2.8	16.5 ± 2.1	100 ± 4.0	225 ± 14	722 ± 29	...	...	...	...	...	...	...	26.0 $\pm$ 1.0	102 ⁺²¹ ₋₁₆	1041 ⁺⁴⁴⁰ ₋₂₄₄	2905 ⁺⁹⁴⁶ ₋₅₇₈	246 ⁺⁵¹ ₋₄₀	...	4213 ⁺¹³⁷¹ ₋₈₃₉
J0845-0123	98 $\pm$ 18	49.7 ± 9.0	12.1 ± 2.5	100 ± 17	232 ± 5	697 ± 15	...	...	...	...	...	...	...	85.6 $\pm$ 1.6	210 ⁺³¹ ₋₂₅	661 ⁺⁶⁰ ₋₅₁	2000 ⁺¹⁸⁸ ₋₁₅₉	357 ⁺³² ₋₂₈	...	2952 ⁺²⁷⁷ ₋₂₃₅

Note. Columns (2)–(14) show the line fluxes normalized by H β . “<” indicates the 1σ upper limit. Columns (16)–(21) show the EWs. We present the median value and 16th and 84th percentiles for the EW measurements.

^a The EWs([O III] $\lambda 5007$) of J1000+0211 and J0845-0123 are reported to be $6000 \pm 2000 \text{ \AA}$ and $4500 \pm 500 \text{ \AA}$, respectively, in Y. Matsuoka et al. (2018).

Table 3
Properties of Our [O III] Emitters

	CEERS-3506	J1000+0211	J0845–0123
$T_e(\text{O III})$ (K)	$20,700 \pm 500$	$16,000 \pm 2000$	$13,700 \pm 700$
n_e^a (cm^{-3})	5000 ± 4000	Assumed 1000	Assumed 1000
$12 + \log(\text{O}/\text{H})$	7.52 ± 0.02	7.81 ± 0.12	8.02 ± 0.06
	$(0.07 \pm 0.01 Z_\odot)$	$(0.13 \pm 0.04 Z_\odot)$	$(0.22 \pm 0.03 Z_\odot)$
$\log(U)^b$	...	–1.91	–2.04

Notes.

^a Measured from [S II] $\lambda\lambda 6717, 6731$. For J1000+0211 and J0845–0123, n_e is assumed to be 1000 cm^{-3} .

^b Measured from [O III] $\lambda 5007$ /[O II] $\lambda\lambda 3727, 29$ and the metallicities with L. J. Kewley et al. (2019) calibration of Equation (3).

The three sources are relatively compact and isolated. Consequently, we employ a circular aperture of approximately $1''.5$ in diameter for photometric analysis of all images, complemented by a slightly larger annulus for background subtraction and uncertainty estimation. The photometric measurements are performed using Photutils (L. Bradley et al. 2024).

3. Results

3.1. Emission Lines

For $\text{H}\beta$, [O III] $\lambda 4959$, and [O III] $\lambda 5007$, we estimate the continuum level with the range of $4800\text{--}5200 \text{ \AA}$, after masking the $\text{H}\beta$ and [O III] $\lambda\lambda 4959, 5007$ doublets emission lines. For the three [O III] emitters, in addition to masking the emission lines, we visually inspect the vicinity of [O III] $\lambda 5007$ to identify and mask the residuals of sky subtraction or the removal of cosmic rays. Assuming the continuum flux density remains constant locally, the continuum underlying the [O III] $\lambda 5007$ emission line is estimated using a Monte Carlo method to account for uncertainties in the continuum flux density. This approach involves generating 10,000 simulated data sets based on the measured continuum flux densities and their associated measurement uncertainties. The median of the posterior predictive probability distribution is adopted as the continuum level at $5007 \text{ \AA}$, with a 68% confidence interval, determined by the 16th and 84th percentiles providing the uncertainty measure. For [O II] $\lambda\lambda 3727, 29$, $\text{H}\alpha$, and other emission lines, the continuum level is determined separately using pixels from their respective nearby continua, excluding regions with known emission lines. The center of the selected range is adjusted slightly based on the spectral coverage limits.

To derive the line fluxes and associated errors, we fit spectral models to the observed spectrum with the error spectrum by the package `lmfit` (M. Newville et al. 2014). Here, the spectral models are composed of a Gaussian model and a constant continuum:

$$f(\lambda) = A \exp\left(-\frac{(x - \mu)^2}{2\sigma^2}\right) + C, \quad (1)$$

with four free parameters of amplitude A , line width σ , central wavelength μ , and offset of continuum C . The prior for the continuum offset C is set based on the values measured from the broad continuum range described in the previous paragraph. We obtain the integrated [O III] $\lambda 5007$ flux by integrating the 5σ width of the Gaussian profile of the [O III] line after subtracting the continuum. We compare the measured Gaussian

flux with the measured integrated flux. If the two fluxes are different by more than 1σ level, a second Gaussian will be added in the fitting. We utilize the same methods to estimate the flux and EW of other lines by masking nearby residuals and other emission lines. Table 2 shows the line ratios of the major narrow component. The unresolved lines (e.g., [O II] $\lambda\lambda 3727, 29$) are presented with integrated measurement.

3.1.1. Balmer Decrement

To assess the effect of dust extinction, we use the Balmer line ratios of $\text{H}\gamma/\text{H}\beta$. $\text{H}\gamma$ and $\text{H}\beta$ are detected in all three studied objects. We obtain the $\text{H}\gamma/\text{H}\beta$ ratios of the narrow components to be 0.45 ± 0.02 , 0.45 ± 0.03 , and 0.50 ± 0.09 , for CEERS-3506, J1000+0211, and J0845–0123, respectively, while the intrinsic ratio is 0.47 for $n_e = 1000 \text{ cm}^{-3}$ and $T_e = 15,000 \text{ K}$ (D. E. Osterbrock & G. J. Ferland 2006). Because the Balmer decrement ratios of $\text{H}\gamma/\text{H}\beta$ align with the intrinsic value within 1σ errors for J1000+0211 and J0845–0123, we do not correct for dust attenuation. In addition, we evaluate the ratio of the narrow component of $\text{H}\alpha/\text{H}\beta$ to be 2.82 ± 0.10 , where the intrinsic ratio is 2.74 for $n_e = 1000 \text{ cm}^{-3}$ and $T_e = 20,000 \text{ K}$ (D. E. Osterbrock & G. J. Ferland 2006). Because the difference falls in the 1σ error, we again do not correct for dust attenuation in CEERS-3506. In summary, we consider the dust attenuation to be negligible for all three objects.

3.1.2. Chemical Properties

In all the objects we study, the auroral lines of [O III] $\lambda 4363$ are detected, enabling us to calculate the oxygen abundances by using the direct method (e.g., see Y. Isobe et al. 2022 for reference). Practically, we use the python package `PyNeb`²³ (V. Luridiana et al. 2015) to conduct the calculation. The electron temperature of O^{2+} , $T_e(\text{O III})$, and the electron density, n_e , are iteratively calculated with the emission line ratios of [O III] $\lambda 4363$ /[O III] $\lambda 5007$ and [S II] $\lambda 6717$ /[S II] $\lambda 6731$, respectively. For J1000+0211 and J0845–0123, the [S II] $\lambda\lambda 6717, 6731$ doublets are undetected. The [O II] $\lambda\lambda 3727, 29$ doublets are unresolved in the deep VPH850 grism spectra but resolved in the VPH650 grism spectra with less exposure time (2400 s) observed on the same nights. We adopt a standard n_e of 1000 cm^{-3} (D. E. Osterbrock & G. J. Ferland 2006). The assumption leads to the ratio of [O II] $\lambda 3727$ to [O II] $\lambda 3729$ to be 1.2 at the temperature of $15,000 \text{ K}$,²⁴ which is consistent with the observed line ratios in the VPH650 spectra for both objects. We proceed the calculation of $T_e(\text{O III})$ with the assumed n_e and the measured line ratios of [O III] $\lambda 4363$ /[O III] $\lambda 5007$. Notably, variations in n_e do not largely affect the determination of $T_e(\text{O III})$. We utilize the line ratios of [O III] $\lambda 5007/\text{H}\beta$ to calculate the O^{2+}/H^+ abundance at given $T_e(\text{O III})$ for each object.

To estimate the O^+/H^+ abundance, we need to assess the electron temperature of O^+ , $T_e(\text{O II})$. Because we cannot directly measure the $T_e(\text{O II})$, we conduct an estimation by using the following empirical relation (D. R. Garnett 1992):

$$T_e(\text{O II}) = 0.7 \times T_e(\text{O III}) + 3000. \quad (2)$$

For J1000+0211 and J0845–0123, we derive the O^+/H^+ from [O II] $\lambda\lambda 3727, 29/\text{H}\beta$ and $T_e(\text{O II})$, while for CEERS-3506 we

²³ https://morisset.github.io/PyNeb_Manual/html/

²⁴ This value is obtained from `PyNeb`.

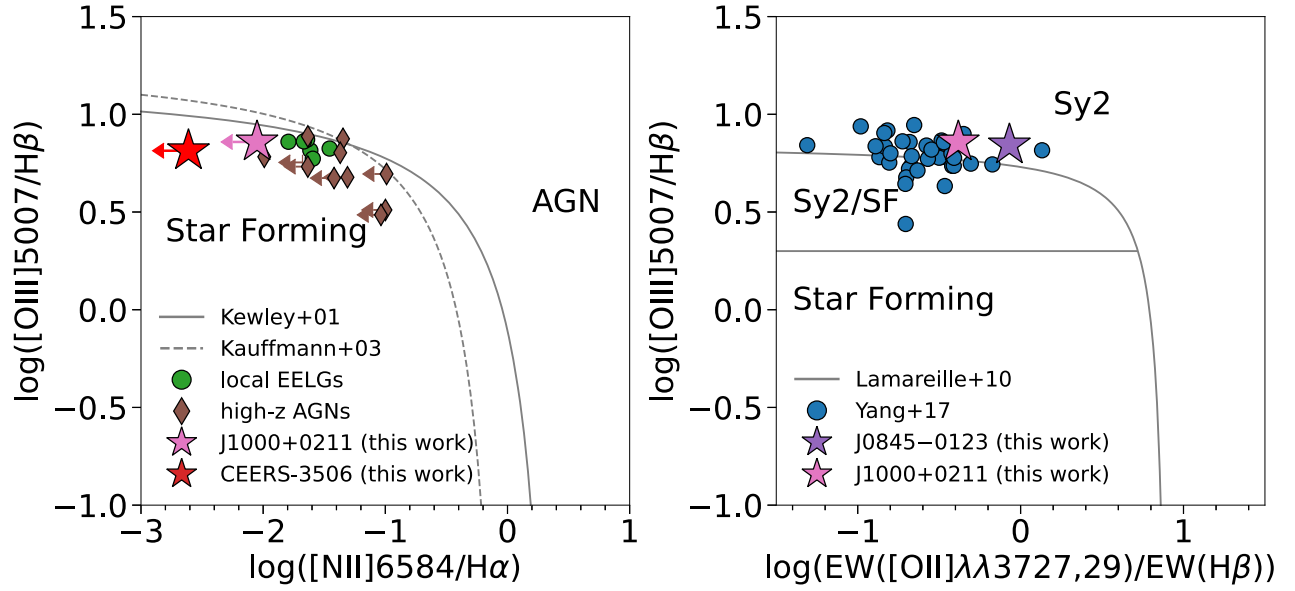


Figure 3. BPT diagram (left) and the blue diagram (right) for our objects. Left panel: the red and pink stars denote the results of J1000+0211 and CEERS-3506 measured in this work, respectively. The green circles represent local EELGs (A. E. Jaskot & M. S. Oey 2013). The brown diamonds represent high- z AGNs from Y. Harikane et al. (2023) and J. Chisholm et al. (2024). We use the arrows if only upper limits can be constrained. The solid and dashed lines are the separation lines recommended by L. J. Kewley et al. (2001) and G. Kauffmann et al. (2003), respectively. Right panel: the purple and pink stars denote the results of J0845-0123 and J1000+0211 measured in this work, respectively. The blue circles denote the “blueberry” galaxies with high $\text{EW}([\text{O III}])$ from H. Yang et al. (2017). The solid lines are the separation lines suggested in F. Lamareille (2010). Similar to local EELGs and high- z AGNs, our objects are located on the border between the star formation and AGN regions in both diagrams.

use $[\text{O II}] \lambda\lambda 7320, 30/\text{H}\beta$ to calculate the O^+ abundance. We obtain the metallicity $12 + \log(\text{O}/\text{H})$ by adding the abundance of O^+ to O^{2+} . We present the results in Table 3.

The ionization parameter, denoted as $\log(U)$, is estimated through diagnostic line ratios. These ratios are calibrated and fitted using a bicubic surface function (L. J. Kewley et al. 2019):

$$z = A + Bx + Cy + Dxy + Ex^2 + Fy^2 + Gxy^2 + Hyx^2 + Ix^3 + Jy^3, \quad (3)$$

where $x = \log(\text{line ratio})$, $y = \log(\text{O}/\text{H}) + 12$, and $z = \log(U)$. The coefficients ($A = 13.8$, $B = 9.5$, $C = -4.3$, $D = -2.4$, $E = -0.58$, $F = 0.28$, $G = 0.16$, $H = 0.089$, $I = 0.031$, and $J = 0.0$) refer to L. J. Kewley et al. (2019). For J1000+0211 and J0845-0123, we apply the line ratio of $[\text{O III}] \lambda 5007/[\text{O II}] \lambda\lambda 3727, 29$ (O32). For CEERS-3506, the $[\text{O II}] \lambda\lambda 3727, 29$ lines are not covered by observations. Additionally, its metallicity falls beyond the valid calibration range established by L. J. Kewley et al. (2019). Hence, the estimation of CEERS-3506 is not conducted. The chemical properties are summarized in Table 3.

3.1.3. Line Diagnostics

Figure 3 shows the BPT (J. A. Baldwin et al. 1981) and blue (F. Lamareille 2010) diagrams. We find that the three EELGs are located near the border between star formation and AGN regions, implying that line diagnostics is insufficient to determine the physical origins.

3.2. Broad Component Identification

In Figures 4 and 5, we present the best-fit models and the observed spectra for the strong emission lines of our three

objects. We define a multi-Gaussian model as

$$f(\lambda) = \sum_{i=1}^N A_i \exp\left(-\frac{(x - \mu_i)^2}{2\sigma_i^2}\right) + C, \quad (4)$$

where $\sigma_j < \sigma_k$ if $j < k$. In this model, N represents the number of Gaussian components, with each component defined by its amplitude A_i , central wavelength μ_i , and line width σ_i . The variable C denotes the common continuum across all components. To identify whether there exist multiple components in the emission lines, we use single ($N=1$) and double ($N=2$) Gaussian models, and fit the models to the strong emission lines of $\text{H}\beta$ and $[\text{O III}] \lambda 5007$ for all three galaxies. We additionally fit the emission lines of $\text{H}\alpha$, $\text{He I } \lambda 10830$, and $\text{Pa}\beta$ for CEERS-3506, while J1000+0211 and J0845-0123 do not have spectra with enough sensitivity whose wavelength coverage goes beyond $\sim 5500 \text{ \AA}$ in the rest frame. For simplicity, we refer to the first and second Gaussian components in the double Gaussian model as the narrow and broad components, respectively. In addition, we require that the full width at half maximum (FWHM), determined by $\text{FWHM} = 2\sqrt{2 \ln 2} \cdot \sigma$ for the Gaussian distribution, satisfies $\text{FWHM}_{\text{narrow}} < 500 \text{ km s}^{-1}$ for the narrow component and $\text{FWHM}_{\text{broad}} > 500 \text{ km s}^{-1}$ for the broad component.

To choose the best models from the single and double Gaussian models, we use the Akaike information criterion (AIC; H. Akaike 1974), which is defined by $\text{AIC} = -2 \log(L) + 2k$. Here, L represents the likelihood of the model, and k denotes the number of parameters in the model. We define the criteria for an emission line to be better explained by a double Gaussian model with $\Delta \text{AIC}_{\text{double-single}} < -10$ and $\text{S/N}_{\text{broad}} > 5$, where $\Delta \text{AIC}_{\text{double-single}}$ is defined by the AIC of the double Gaussian model subtracted by that of the single Gaussian model, and $\text{S/N}_{\text{broad}}$ is the signal-to-noise ratio (S/N) of the broad

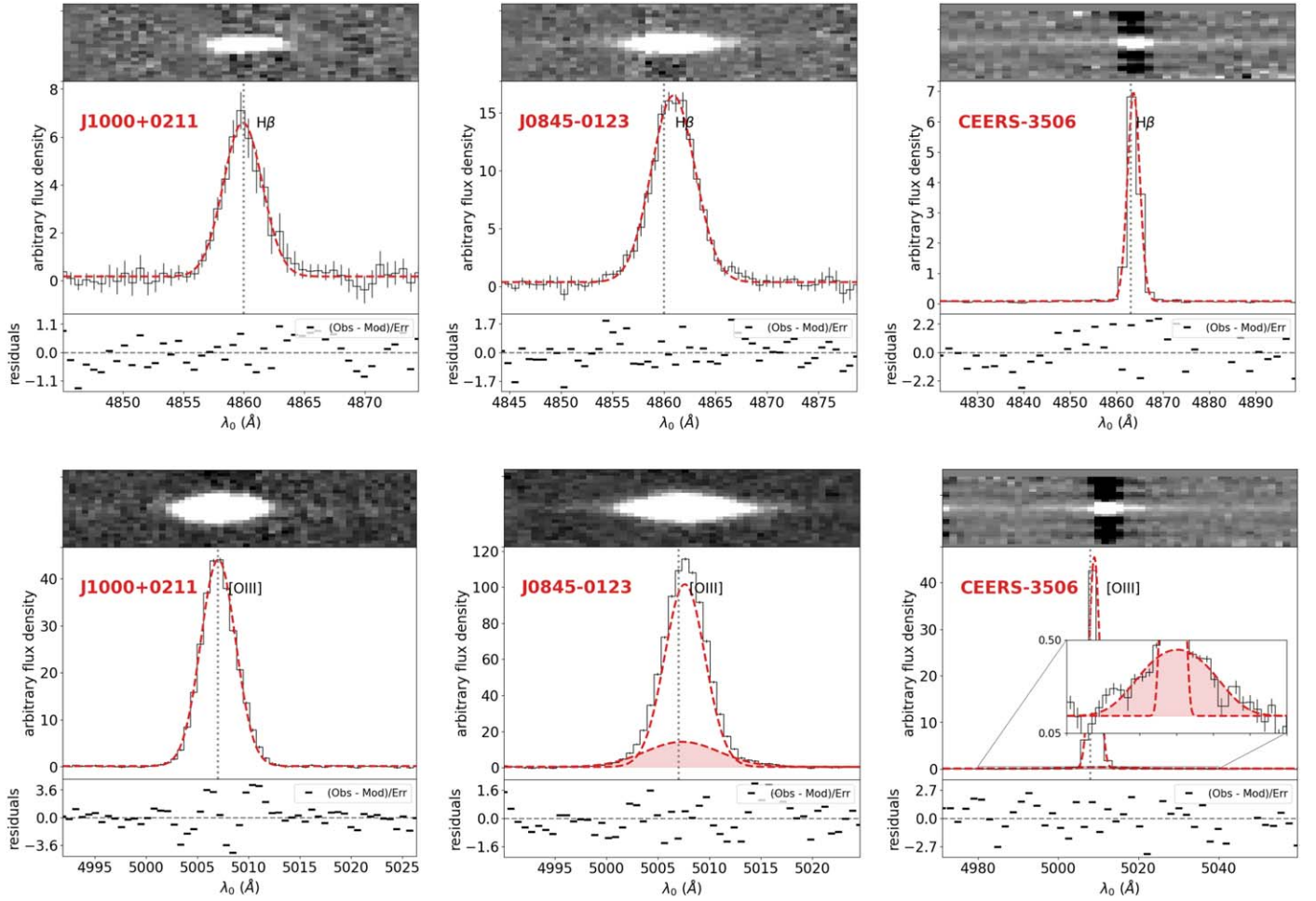


Figure 4. Strong $H\beta$ and $[O\text{ III}]\lambda 5007$ emission lines of the three $[O\text{ III}]$ emitters. Top panels: $H\beta$ lines for J1000+0211, J0845–0123, and CEERS-3506 from left to right. The black and red lines indicate the observed spectra and best-fit models, respectively. The vertical dotted lines denote the systemic redshifts. The 2D spectra and the fitting residuals are shown above and below the main panels, respectively. The horizontal dotted lines in the residual panels denote the value of 0. Bottom panels: the same as the top panels, but for $[O\text{ III}]\lambda 5007$ lines. We mark the best-fit broad components with red shading. For clarity, CEERS-3506 is shown with a detailed view in the zoomed-in inset. The inset uses a logarithmic scale to highlight the faint broad component. The best-fit parameters for the fitting are presented in Table 4.

component. We confirm that these criteria work properly by visually inspecting the distribution of the residuals of data to the best-fit double Gaussian model.

The broad component is attributed to the broad-line region (BLR) of an AGN or the galactic outflow because the gas motion of the BLR/outflow is faster than the interstellar medium and/or narrow-line region, which are represented by the narrow component. Note that a type 1 AGN does not show broad forbidden lines (e.g., $[O\text{ III}]\lambda 5007$) but broad permitted lines (e.g., $H\beta$ and $H\alpha$), because the electron density in the BLR is higher than the critical densities of forbidden lines. Unlike BLRs, outflows produce both broad forbidden lines and broad permitted lines because the electron density is lower than the critical density.

3.2.1. $[O\text{ III}]\lambda 5007$ Lines

Because the BLR of an AGN does not produce the broad-line feature in $[O\text{ III}]\lambda 5007$, we search for outflow signatures with the strong $[O\text{ III}]\lambda 5007$ emission lines in our three galaxies. We evaluate the $\Delta\text{AIC}_{\text{double-single}}$ values to be +5.3, –75.8, and –68.1 for J1000+0211, J0845–0123, and CEERS-3506, respectively, while our criterion is $\Delta\text{AIC}_{\text{double-single}} < -10$. We obtain the S/N_{broad} to be 5.7 for J0845–0123 and 12.6 for

CEERS-3506, which satisfy our requirement for the S/N ($S/N_{\text{broad}} > 5$). Therefore, we conclude that one out of the three EELGs, J1000+0211, does not have a broad component in $[O\text{ III}]\lambda 5007$ emission lines. The other two galaxies, J0845–0123 and CEERS-3506, have broad components with $\text{FWHM}_{\text{outflow}} = \text{FWHM}_{\text{broad}, [O\text{ III}]} = 507 \pm 38 \text{ km s}^{-1}$ and $1093 \pm 107 \text{ km s}^{-1}$, respectively. Details of the fitting results are presented in Table 4. Moreover, we fit $[O\text{ III}]\lambda 4959$ with the same FWHM as that of $[O\text{ III}]\lambda 5007$. We find that the flux ratios of the broad $[O\text{ III}]\lambda 4959$ to $[O\text{ III}]\lambda 5007$ lines are 3.1 ± 1.1 and 3.2 ± 1.4 for J0845–0123 and CEERS-3506, respectively. These values are consistent with the intrinsic ratio of 3 predicted by atomic physics, further confirming the presence of a broad component in the $[O\text{ III}]\lambda 5007$ lines for both objects. Notably, the outflow velocity of CEERS-3506 is larger than a typical starburst-driven outflow velocity ($\sim 500 \text{ km s}^{-1}$; S. Veilleux et al. 2005; T. M. Heckman et al. 2015), suggesting the presence of other drivers (e.g., AGNs) in CEERS-3506.

3.2.2. $H\beta$ Lines

For the one galaxy with no outflow signature, J1000+0211, we apply the single and double Gaussian models to the $H\beta$ line. The results prefer the single Gaussian model ($\Delta\text{AIC}_{\text{double-single}} = 5.3$).

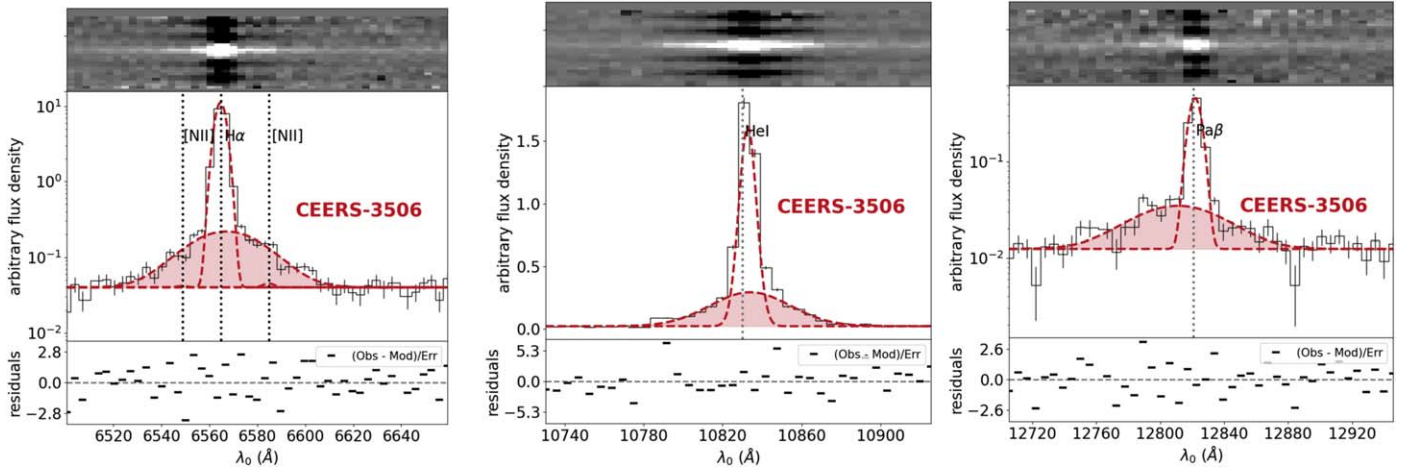


Figure 5. The same as Figure 4, but for $H\alpha$, $He\ I\ \lambda 10830$, and $Pa\beta$ lines of CEERS-3506 that have deep spectra obtained with JWST/NIRSpec beyond the rest-frame $0.6\ \mu m$ (see J1000+0211 and J0845–0123). The left and right panels are shown in a logarithmic scale.

For the two galaxies with outflow signatures, J0845–0123 and CEERS-3506, we calculate the $\Delta AIC_{\text{double-single}}$ values for the $H\beta$ lines to be -12.4 and -6.5 , respectively. Notably, CEERS-3506 does not satisfy our AIC criterion of $\Delta AIC_{\text{double-single}} < -10$. The S/N_{broad} values for the $H\beta$ lines are 2.2 and 3.2, both of which fall below the significance threshold of $S/N > 5$. Thus, we conclude that no reliable broad components in $H\beta$ are detected for either J0845–0123 or CEERS-3506. We summarize the parameters of the best-fit models in Table 4.

3.2.3. Other Lines of CEERS-3506

For CEERS-3506, the spectra are sensitive enough for us to investigate other permitted lines, $H\alpha$, $He\ I\ \lambda 10830$, and $Pa\beta$. We search for the outflow and/or BLR emission of these permitted lines in CEERS-3506.

We have detected a broad component in $[O\ III]\ \lambda 5007$, suggesting the presence of an outflow in CEERS-3506. However, the broad-to-narrow flux ratio of $[O\ III]\ \lambda 5007$ is notably low at 0.05. There is a possibility that the outflow signals may not be detected in other lines (like $H\beta$ discussed above; see S. Carniani et al. 2015). Hence, out of practical feasibility, we first compare the single and double Gaussian models. If the double Gaussian model fits better than the single Gaussian model, we then conduct a comparative analysis with the double and triple ($N=3$) Gaussian models. Here, we define $\Delta AIC_{\text{triple-double}} = AIC_{\text{triple}} - AIC_{\text{double}}$, and require $\Delta AIC_{\text{triple-double}} < 0$ to choose the triple Gaussian model as the best fit.

For the $H\alpha$ of CEERS-3506, we simultaneously fit the $H\alpha$ and $[N\ II]\ \lambda\lambda 6548, 84$ lines. We fix the wavelength difference between $[N\ II]\ \lambda\lambda 6548, 84$ and $H\alpha$, set the FWHMs of $[N\ II]\ \lambda\lambda 6548, 6584$ to be the same as the narrow component of $H\alpha$, and fix the flux ratio of $[N\ II]\ \lambda 6548$ to $[N\ II]\ \lambda 6584$ at 0.327 (D. E. Osterbrock & G. J. Ferland 2006), as this ratio is insensitive to both electron temperature and density. For all of the permitted lines of $H\alpha$, $He\ I\ \lambda 10830$, and $Pa\beta$ of CEERS-3506, we calculate the $\Delta AIC_{\text{double-single}} = AIC_{\text{double}} - AIC_{\text{single}}$ values to be -85.1 , -77.9 , and -40.7 , and find that all of these lines have significant broad components with $S/N_{\text{broad}} = 13.6$, 18.7 , and 7.1 , respectively. All of these three lines meet our criteria for preferring the double Gaussian models ($\Delta AIC_{\text{double-single}} < -10$ and $S/N_{\text{broad}} > 5$; see above). We

proceed with the analysis of the triple Gaussian models. Consequently, we obtain the values of $\Delta AIC_{\text{triple-double}}$ to be $+2.4$, $+3.8$, and $+6.5$, for $H\alpha$, $He\ I\ \lambda 10830$, and $Pa\beta$, respectively. The values of $\Delta AIC_{\text{triple-double}}$ do not meet the criterion of $\Delta AIC_{\text{triple-double}} < 0$; we conclude that the triple Gaussian models are not preferable for the three permitted lines, but the double Gaussian models are. We show the fitting results in Table 4.

The $FWHMs_{\text{broad}}$ are 1659 ± 116 , 1325 ± 67 , and $1513 \pm 219\ km\ s^{-1}$ for $H\alpha$, $He\ I\ \lambda 10830$, and $Pa\beta$, respectively, while $FWHM_{\text{outflow}}$ is $1093 \pm 107\ km\ s^{-1}$ in the $[O\ III]\ \lambda 5007$ line. Additionally, the broad-to-narrow flux ratios of $H\alpha$ and $Pa\beta$ are 0.11 and 0.35, respectively, while that of $[O\ III]\ \lambda 5007$ is 0.05. Typically, outflows show a stronger broad-to-narrow ratio for $[O\ III]\ \lambda 5007$ compared to $H\alpha$ (M. A. Marshall et al. 2023). The differences in FWHMs between the $[O\ III]\ \lambda 5007$ line and hydrogen lines ($H\alpha$ and $Pa\beta$), as well as the smaller broad-to-narrow ratios for the $[O\ III]\ \lambda 5007$ line compared to the hydrogen lines, suggest the different origins of the broad components detected in the hydrogen lines from that of $[O\ III]\ \lambda 5007$. The $He\ I\ \lambda 10830$ line is influenced by multiple factors, including recombination, collisional excitation, and its optical thickness, complicating the interpretation of its broad-to-narrow ratio. However, the detection of a high-velocity broad component in $He\ I\ \lambda 10830$ is consistent with the presence of an AGN.

In addition, we find that the broad-to-narrow ratios of the hydrogen lines increase as the wavelength increases ($H\alpha$: 0.11 ± 0.01 ; $Pa\beta$: 0.35 ± 0.05), implying that the dust attenuation of broad lines differs from that of narrow lines. This phenomenon can be better explained by the scenario in which the broad components of the hydrogen lines come from the BLR partly obscured by the dust torus, rather than attributing the broad hydrogen lines to outflow emission.

In summary of our analysis of the three permitted lines, we decide to choose the double Gaussian model as the best-fit model for $H\alpha$, $He\ I\ \lambda 10830$, and $Pa\beta$ of CEERS-3506, and we prefer the hypothesis that the broad components of the hydrogen lines come from the BLR. However, whether the origin of the broad components in the hydrogen lines is the outflow or BLR does not change our main conclusion that CEERS-3506 harbors AGNs.

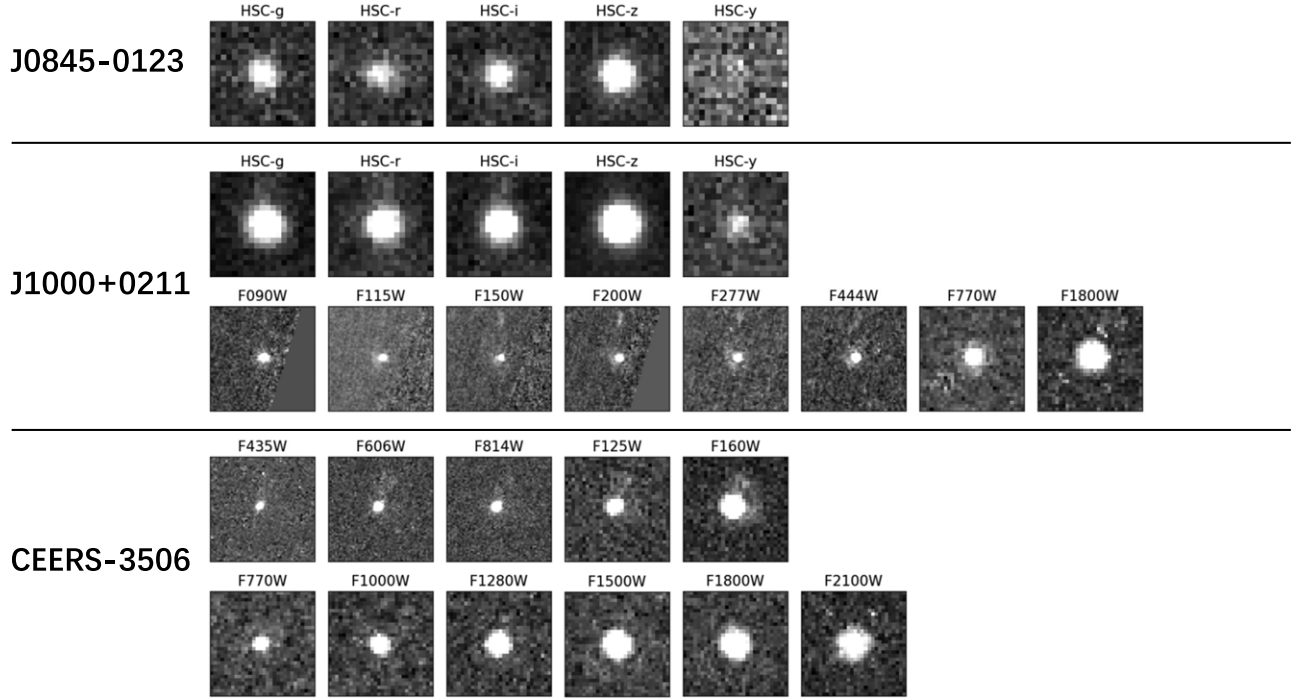


Figure 6. $1''.5 \times 1''.5$ images of our [O III] emitters. The Subaru/HSC g , r , i , z , and y thumbnail cutouts are shown for J0845 – 0123. We collect the Subaru/HSC g , r , i , z , and y bands, the JWST/NIRCam F090W, F115W, F150W, F200W, F277W, and F444W, and the JWST/MIRI F770W and F1800W thumbnail cutouts for J1000 +0211. For CEERS-3506, the JWST/NIRCam images are not available, so we instead show the HST/ACS F435W, F606W, and F814W, and the HST/WFC3 F125W and F160W images together with the JWST/MIRI F770W, F1000W, F1280W, F1500W, and F1800W, and the F2100W cutouts.

Table 4
Best-fit Line Profiles of Our [O III] Emitters

ID	Line	$\text{FWHM}_{\text{narrow}}$ (km s^{-1})	$\text{FWHM}_{\text{broad}}$ (km s^{-1})	$\text{S/N}_{\text{broad}}$	$\text{Flux}_{\text{broad}}/\text{Flux}_{\text{narrow}}$	Δv_{broad} (km s^{-1})	ΔAIC
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
J1000+0211	$\text{H}\beta$	235 ± 9	...	...	...	...	+5.3
	[O III] $\lambda 5007$	240 ± 2	...	...	...	...	+1.2
J0845–0123	$\text{H}\beta$	272 ± 17	...	...	...	...	–12.4
	[O III] $\lambda 5007$	273 ± 6	507 ± 38	5.7	0.25 ± 0.05	-16 ± 7	–75.8
CEERS-3506	$\text{H}\beta$	228 ± 4	...	...	...	...	–6.5
	[O III] $\lambda 5007$	214 ± 4	1093 ± 107	12.6	0.04 ± 0.00	74 ± 34	–68.1
	$\text{H}\alpha$	241 ± 3	1659 ± 116	13.6	0.11 ± 0.01	108 ± 40	–85.1
	He I $\lambda 10830$	296 ± 13	1325 ± 67	18.7	0.77 ± 0.05	-10 ± 50	–77.9
	$\text{Pa}\beta$	214 ± 7	1513 ± 219	7.1	0.35 ± 0.05	-260 ± 110	–40.7

Note. Column (3): FWHM of the narrow component. Column (4): FWHM of the broad component ($\text{FWHM}_{\text{broad}} > \text{FWHM}_{\text{narrow}}$). Column (5): S/N of the broad component. Column (6): the flux ratio between the broad and narrow components. Column (7): $(\mu_{\text{broad}} - \mu_{\text{narrow}})/\mu_{\text{narrow}} \times c$: the central velocity offset of the broad component compared to the narrow component. Column (8): $\text{AIC}_{\text{double}} - \text{AIC}_{\text{single}}$: a more negative value indicates a stronger preference for the double Gaussian model over the single Gaussian model.

3.3. SED Fitting and Photometric Results

Figure 6 shows the cutouts of our three [O III] emitters in multiwavelength bands. We use the `Photutils`²⁵ python package to perform the aperture photometry measurement and error estimation. We employ the `CIGALE` code (M. Boquien et al. 2019) to conduct the spectral energy distribution (SED) fitting. The `CIGALE` code obtains the best-fit model spectra with the least reduced χ^2 method. For J1000+0211 and CEERS-3506, we have multiwavelength photometry data from the rest-frame UV to the mid-infrared. To exploit this rich data

set, we combine the following `CIGALE` modules: `sfhdelayed`, `bc03`, `nebular`, `dustatt_modified_starburst`, `dale 2014`, `skirtor2016`, `restframe_parameters`, and `redshifting`. With these modules, our models combine stellar emission, nebular emission, dust emission, AGN contribution, and dust attenuation. We perform SED fitting to complement our spectroscopic results, primarily to constrain stellar properties and secondarily to detect AGN IR emission. To confirm that the IR excess originates from the AGN, we include dust emission even though the dust content is suggested to be negligible in our spectroscopic result. The parameters for redshift, metallicity, and dust attenuation are fixed based on spectroscopic measurements. The specific parameter configurations we focus on are detailed in

²⁵ <https://photutils.readthedocs.io/>

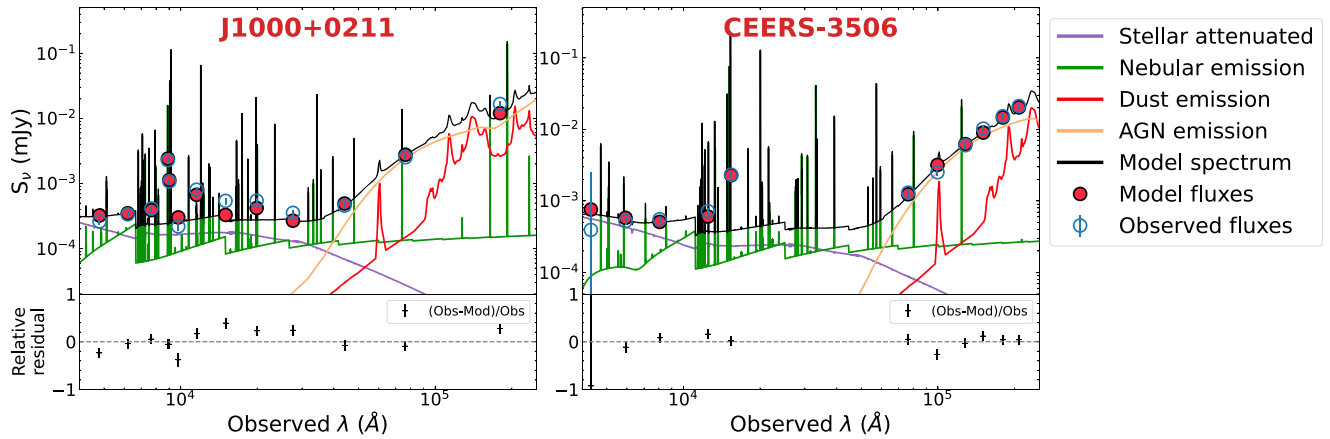


Figure 7. CIGALE SED fitting results of the two [O III] emitters, J1000+0211 (left) and CEERS-3506 (right). The blue open and red filled circles mark the observed fluxes and the model fluxes, respectively. The solid lines mark the best-fit models of the total spectrum (black), stellar continuum (purple), nebular emission (green), AGN emission (orange; including emission from surrounding dust torus), and the dust emission (red; dust heated by stars). Both J1000+0211 and CEERS-3506 display the near-infrared excess ($\gtrsim 2 \mu\text{m}$ in the rest frame), suggesting the existence of hidden AGNs complemented by our spectroscopic measurements. The bottom panels are the relative residuals.

Table 5
Initial Setup for CIGALE Modules

Parameter	Description	Values
tau_main	e -folding time (τ) of the main stellar population model in Myr	50, 100, 200, 500, 1000, 2000, 4000, 8000, 10000, 20000, 50000
age_main	Age of the main stellar population in the galaxy in Myr	1, 2, 3, 4, 5, 6, 7, 8, 9, 10
imf	Initial mass function	G. Chabrier (2003)
f_burst	Mass fraction of the late burst population	0.0
fracAGN	Fraction of AGN IR luminosity to total IR luminosity	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 0.99
oa	Angle measured between the equatorial plane and edge of the torus	40
i	Viewing angle, the position of the instrument with respect to the AGN axis	90, 70, 50
alpha	alpha slope of dust emission in the D. A. Dale et al. (2014) model.	1.0, 2.0, 4.0

Note. We use the module `sfhdelayed` and $\text{SFR}(t) \propto \frac{t}{\tau^2} \exp(-t/\tau)$.

Table 5. We adopt the default values from CIGALE for other parameters.

We present model spectra in Figure 7 and list the properties derived from the SED analysis in Table 6. We use the stellar age constrained by SED fitting in Section 4.2. Most importantly, we detect the near-infrared excess in the MIRI data for both objects, while we infer the negligible dust content from the Balmer decrements of the narrow-line components (see Section 3.1.1). This indicates the existence of AGNs for both objects, which supports our argument in Section 3.2.3. Plus, our SED fitting results suggest that the two systems are AGN dominated with fractions of AGN infrared luminosity to total infrared luminosity at 0.6 and 0.8 for CEERS-3506 and J1000+0211, respectively. Assuming the Eddington ratios to be 1, we utilize the bolometric luminosity of the SED models to calculate the black hole masses of CEERS-3506 and J1000+0211. The resulting black hole masses are $\log(M_{\text{SED}}/M_{\odot}) = 6.70$ and 5.95, respectively.

For J0845–0123, due to the absence of photometric data beyond the rest-frame $0.6 \mu\text{m}$, which are key to constraining the contribution of long-lived, low-mass stellar populations, a precise estimate on the physical properties with SED fitting is challenging. We present the model spectra in Figure 8 as a reference. It is crucial to note that the properties of J0845

–0123 carry significant systematics due to the inadequacy of photometric data points.

3.4. Surface Brightness Profiles

We compare the objects’ surface brightness (SB) profiles with the point-spread function (PSF). This analysis is limited to space telescope images to enhance spatial resolution. To minimize the emission line contamination from the [O III] and Balmer lines, we use the HST ACS F435W image (rest frame: $0.13\text{--}0.16 \mu\text{m}$) for CEERS-3506 and the JWST NIRC2 F150W image (rest frame: $0.73\text{--}0.91 \mu\text{m}$) for J1000+0211, respectively. We do not perform the analysis for J0845–0123 because we only have ground-based Subaru-HSC photometric data for it. We employ the `Galight` package for SB measurement (X. Ding et al. 2021, 2022). To obtain the empirical PSF of the two objects, we select the nearest stars with the `Galight` search algorithm²⁶ and subsequently manually inspect them. For J1000+0211, we verify that our PSF candidate is a star in the COSMOS2020 catalog (J. R. Weaver et al. 2022). The radial profile comparisons between our [O III] emitters and these PSF references are illustrated in Figure 9. Plus, we find that changing the PSF

²⁶ <https://github.com/dartoon/galight>

Table 6
Properties of Our [O III] Emitters Derived from SED Fitting

ID	SFR ($M_{\odot} \text{ yr}^{-1}$)	Age (Myr)	$\log(M_{*}/M_{\odot})$	$\log(M_{\text{SED}}/M_{\odot})^{\text{a}}$	$f_{\text{AGN}}^{\text{b}}$	Reduced χ^2_{c}
CEERS-3506	60 ± 35	2.0 ± 0.7	8.07 ± 0.03	6.70 ± 0.02	0.6	1.2
J1000+0211	3.0 ± 0.3	3.1 ± 0.3	7.08 ± 0.02	5.95 ± 0.07	0.8	4.1
J0845–0123 ^d	6.1 ± 2.7	1.5 ± 0.5	6.96 ± 0.06	...	...	2.7

Notes. SFR: star formation rate.

^a This value is calculated based on the total disk luminosity estimates from the AGN emission module (`skitor2016`) of CIGALE. We assume an Eddington ratio of 1 to calculate the referential values.

^b Fractions of the AGN infrared luminosity to the total infrared luminosity.

^c Reduced χ^2 values for the best-fit SED models.

^d The derived properties of J0845–0123 have significant systematics because of the lack of the rest-frame infrared bands.

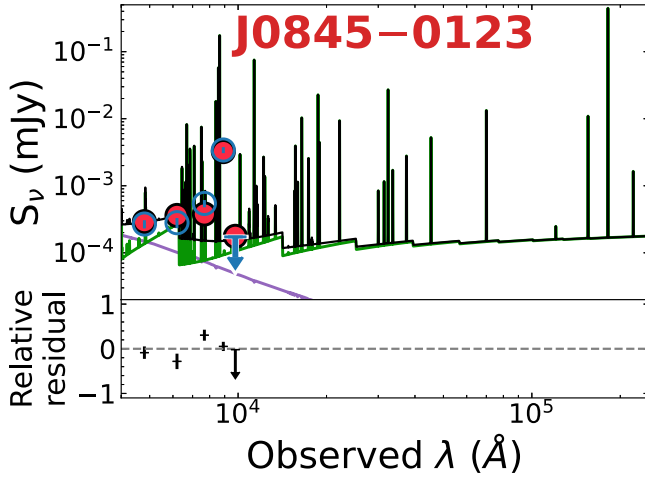


Figure 8. The same as Figure 7 but for J0845–0123. The arrow indicates a 1σ upper limit.

representative does not make a large difference in our comparison.

Based on the SB profiles obtained in Figure 9, we calculate the concentration index defined as $c = R_{90}/R_{50}$ (K. Shimasaku et al. 2001; I. Strateva et al. 2001; S. Shen et al. 2003), where R_{90} and R_{50} are the radii enclosing 90% and 50% of the total flux, respectively. The concentration indices are estimated to be 2.7 and 3.7 for CEERS-3506 and J1000+0211, respectively, while an exponential disk has $c \sim 2.3$ (S. Shen et al. 2003). Thus, we conclude that both objects exhibit compact morphology. The compactness is consistent with the high AGN fraction (CEERS-3506: 0.6; J1000+0211: 0.8; see Section 3.3) suggested by our SED fitting results.

4. Discussion

4.1. AGN Properties

Figure 10 presents the line ratios of broad $H\beta$ ($bH\beta$) and [O III] $\lambda 5007$. The line ratios are related to the AGN subtypes (H. Winkler 1992). The line ratios of Sy1, Sy1.2, Sy1.5, and Sy > 1.8 are indicated in Figure 10, where Sy > 1.8 corresponds to Sy1.8, Sy1.9, and Sy2. We calculate the ratio of the total integrated $H\beta$ flux to [O III] $\lambda 5007$ flux to be 0.15, 0.14, and 0.14 for CEERS-3506, J1000+0211, and J0845–0123, respectively, which are used as the upper limit of the ratio of broad $H\beta$ luminosity to [O III] $\lambda 5007$ luminosity. Comparing the line ratios for these subtypes with our three objects, we

found that all three objects would be classified as Sy > 1.8 subtypes if they are confirmed as AGNs.

We then discuss the AGN properties of CEERS-3506, which has broad $H\alpha$ and $\text{Pa}\beta$ lines that allow us to estimate black hole masses. In the following analysis, we assume that the broad components in the $H\alpha$ and $\text{Pa}\beta$ lines originate from the BLR (Section 3.2.3).

We present the black hole mass of CEERS-3506 estimated by various methods in Table 7 and display the black hole masses and stellar masses in Figure 11. We utilize the relation calibrated at $z \sim 0$ in J. E. Greene & L. C. Ho (2005) for the estimation of the black hole mass:

$$M_{\bullet} = 2.0^{+0.4}_{-0.3} \times 10^6 M_{\odot} \times \left(\frac{L_{\text{H}\alpha, \text{broad}}}{10^{42} \text{ erg s}^{-1}} \right)^{0.55 \pm 0.02} \left(\frac{\text{FWHM}_{\text{H}\alpha, \text{broad}}}{10^3 \text{ km s}^{-1}} \right)^{2.06 \pm 0.06}. \quad (5)$$

We estimate the value of $\log(M_{\bullet}/M_{\odot})$ to be 6.4 ± 0.1 . For comparison, we show the result applying a correction for Sy1.9 AGNs suggested in M. J. Mejia-Restrepo et al. (2022):

$$L(\text{bH}\alpha)_{\text{cor}} = (17 \pm 7.6) \times L(\text{bH}\alpha)_{\text{obs}} \quad (6)$$

$$\text{FWHM}(\text{bH}\alpha)_{\text{cor}} = (1.92 \pm 0.22) \times \text{FWHM}(\text{bH}\alpha)_{\text{obs}}. \quad (7)$$

We estimate the value of $\log(M_{\bullet}/M_{\odot})$ to be 7.6 ± 0.2 . We also utilize the broad $\text{Pa}\beta$ line for the $M_{\bullet}$ estimation, which is calibrated in D. Kim et al. (2010):

$$M_{\bullet} = 10^{7.33 \pm 0.10} M_{\odot} \times \left(\frac{L_{\text{Pa}\beta, \text{broad}}}{10^{42} \text{ erg s}^{-1}} \right)^{0.45 \pm 0.03} \left(\frac{\text{FWHM}_{\text{Pa}\beta, \text{broad}}}{10^3 \text{ km s}^{-1}} \right)^{1.69 \pm 0.16}. \quad (8)$$

We estimate the value of $\log(M_{\bullet}/M_{\odot})$ to be 6.9 ± 0.1 .

We adopt the bolometric luminosity from the SED fitting results to derive the Eddington ratios for different methods by $\lambda_{\text{Edd}} = L_{\text{bol}}/L_{\text{Edd}} = M_{\bullet, \text{SED}}/M_{\bullet}$, where $M_{\bullet, \text{SED}}$ is the black hole mass calculated from the SED fitting results in Table 6.

We calculate the black hole mass to stellar mass ratio, $M_{\bullet}/M_{*}$, to be $M_{\bullet}/M_{*} = 0.02, 0.32$, and 0.08 for the black hole masses of the $H\alpha$, $H\alpha + \text{Sy}1.9$ correction, and $\text{Pa}\beta$ methods, respectively. These ratios fall in the range of 0.02–0.3, which is comparable to that of high- z AGNs, ~ 0.001 –0.2, recently reported by JWST studies (e.g., Y. Harikane et al. 2023; R. Maiolino et al. 2024).

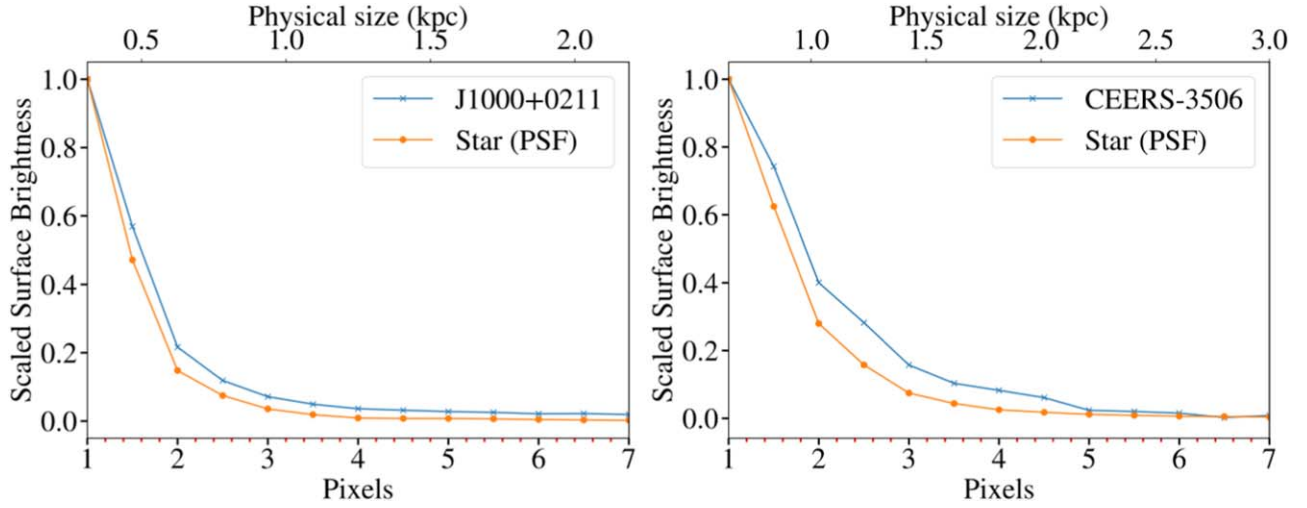


Figure 9. SB profiles (annuli) of CEERS-3506 (left) and J1000+0211 (right) compared with nearest stars. The blue crosses mark the SB within the evenly spaced annuli. The orange crosses denote the closest star representing the PSF. The comparison is conducted with the ACS F435W (λ_0 : 0.13–0.16 μm) image and NIRC2 F150W (λ_0 : 0.73–0.91 μm) image for CEERS-3506 and J1000+0211, respectively. The filters are chosen due to less contamination from the emission lines. This comparison reveals the compactness of J1000+0211 and CEERS-3506.

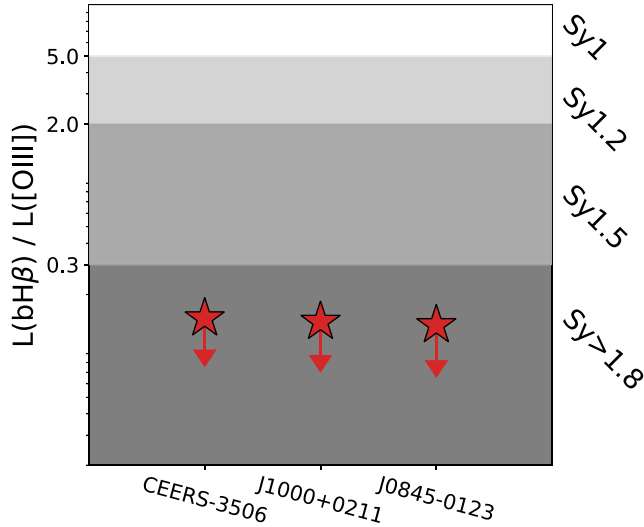


Figure 10. Quantitative classification of AGN subtypes based on the luminosity ratio between the broad H β (bH β) emission and the narrow [O III] $\lambda 5007$ emission (H. Winkler 1992; M. J. Mejia-Restrepo et al. 2022). On the y-axis, we represent this luminosity ratio with the logarithmic scale. The x-axis marks the studied objects' IDs. Since we do not detect broad H β emission in our objects, we plot upper limits using the ratio of the total H β emission (including the narrow line) to the [O III] $\lambda 5007$ emission line.

Table 7

Derived Black Hole Properties of CEERS-3506 with Different Methods

Method	$\log(M_*/M_\odot)$	λ_{Edd}
H α	6.4 ± 0.1	2.06
H α + Sy1.9 correction	7.6 ± 0.2	0.11
Pa β	6.9 ± 0.1	0.46

4.2. Physical Origins of High EW Objects

We use the `Cloudy` photoionization code (vC22; C. M. Gunasekera et al. 2023) to simulate the evolution of EW([O III]). For star formation (SF) models, we utilize the Binary Population and Spectral Synthesis model (BPASS v2.1;

J. J. Eldridge et al. 2017) with an initial mass function (IMF)²⁷ upper slope of -1.3 and an upper stellar mass limit of $100M_\odot$ to generate stellar spectra. We use the models that include binary stars, which are more realistic according to current theory and observation. We change the ionizing parameter $\log U$ from -3.0 to -1.0 by 0.5 and the stellar age from 1 to 20 Myr. For nebular spectra, we set the electron number density $n_e = 1000 \text{ cm}^{-3}$ and the metallicity $Z = 0.1\text{--}1.0Z_\odot$ by $0.1Z_\odot$.

Similarly, we conduct the `Cloudy` simulation with the ionizing source as an AGN. We adopt the typical AGN spectrum:

$$f_\nu = \nu^{\alpha_{uv}} \exp\left(\frac{-h\nu}{kT_{\text{BB}}}\right) \exp\left(\frac{-kT_{\text{IR}}}{h\nu}\right) + a\nu^{\alpha_x}, \quad (9)$$

with the big bump temperature $T_{\text{BB}} = 15,000 \text{ K}$, the low-energy slope of the big bump continuum $\alpha_{uv} = 0.5$, the slope of the X-ray component $\alpha_x = -1$, the assumed big bump infrared exponential cutoff at $kT_{\text{IR}} = 0.01 \text{ Ryd}$, and the coefficient a adjusted to produce the X-ray to UV ratio $\alpha_{ox} = -1.4$ for the case where the big bump does not contribute to the emission at 2 Kev .

In Figure 12, we show the evolution of EW([O III]) as stellar age increases for the SF models. We find that the two objects CEERS-3506 and J0845–0123 agree with the SF models, while it is hard to explain the high EW([O III]) of J1000+0211 using the SF models. In Figure 13, we show the relation between EW([O III]) and metallicity for the SF and AGN models. We find that the obscured AGN models can produce high EW([O III]) when the ionizing parameter is high ($\log U > -2$). Furthermore, we compare the observables of the three [O III] emitters with our models. We find that the obscured AGN model, whose host galaxies have a weak stellar continuum at the rest-frame optical, can produce the high EW([O III]) of our sources.

In addition, J1000+0211 and CEERS-3506 lie within the deep Chandra fields, specifically within the Chandra COSMOS survey (F. Civano et al. 2016; S. Marchesi et al. 2016) and the

²⁷ Recommended IMF by the BPASS team; https://bpass.auckland.ac.nz/8/files/bpassv2_1_manual_accessible_version.pdf.

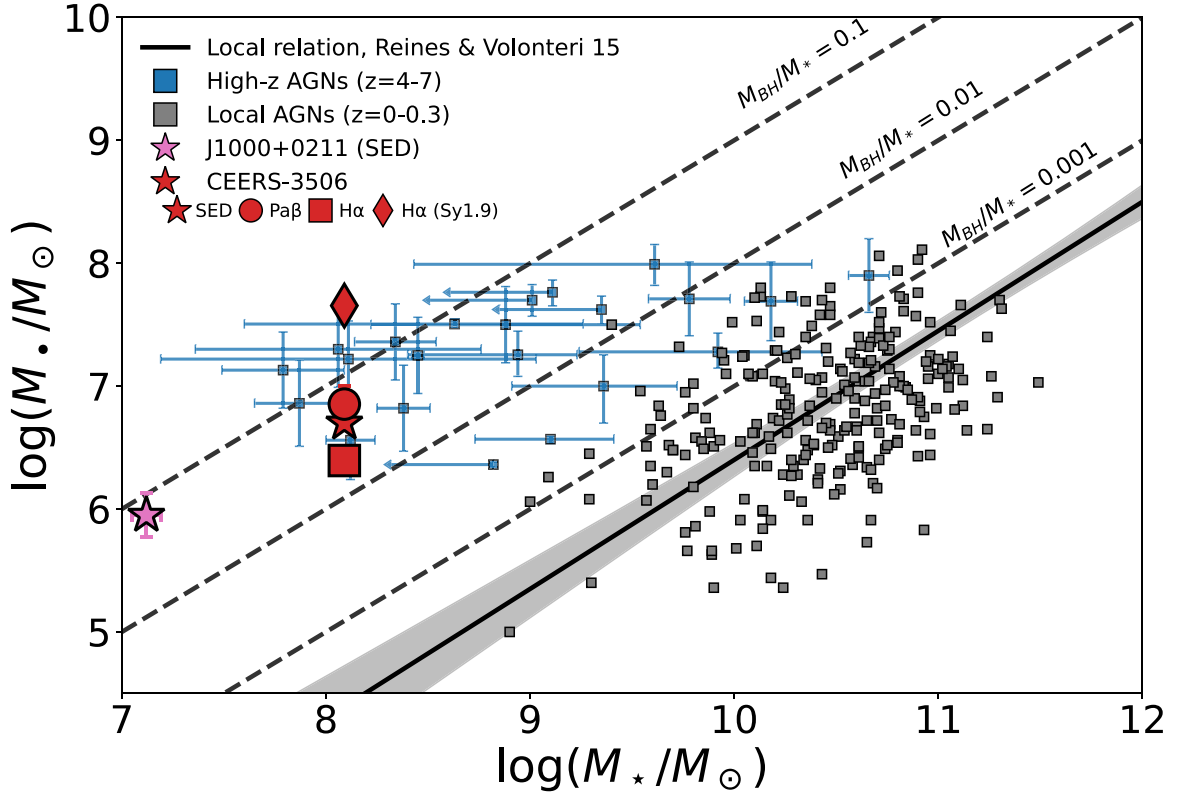


Figure 11. Relation between black hole mass ($M_{\bullet}$) and the host's stellar mass (M_*). The red symbols mark the black hole mass of CEERS-3506 estimated by various methods (star: SED, by assuming $\lambda_{\text{Edd}} = 1$; circle: $\text{Pa}\beta$ calibration; square: $\text{H}\alpha$ calibration; diamond: $\text{H}\alpha$ calibration with Sy1.9 correction). The pink star marks the estimation of J1000+0211 (SED, the same method as CEERS-3506). The blue squares are AGNs at $z = 4-7$ from Y. Harikane et al. (2023) and R. Maiolino et al. (2024). The gray squares mark the local AGNs from C.-T. J. Chen et al. (2017) and A. E. Reines & M. Volonteri (2015). The black line is the local relation (A. E. Reines & M. Volonteri 2015) with the 1σ region marked by gray shading. The dashed lines denote the $M_{\bullet}/M_* = 0.001, 0.01$, and 0.1 . This suggests that our studied objects are AGN dominated and show more similarity to AGNs at high redshift.

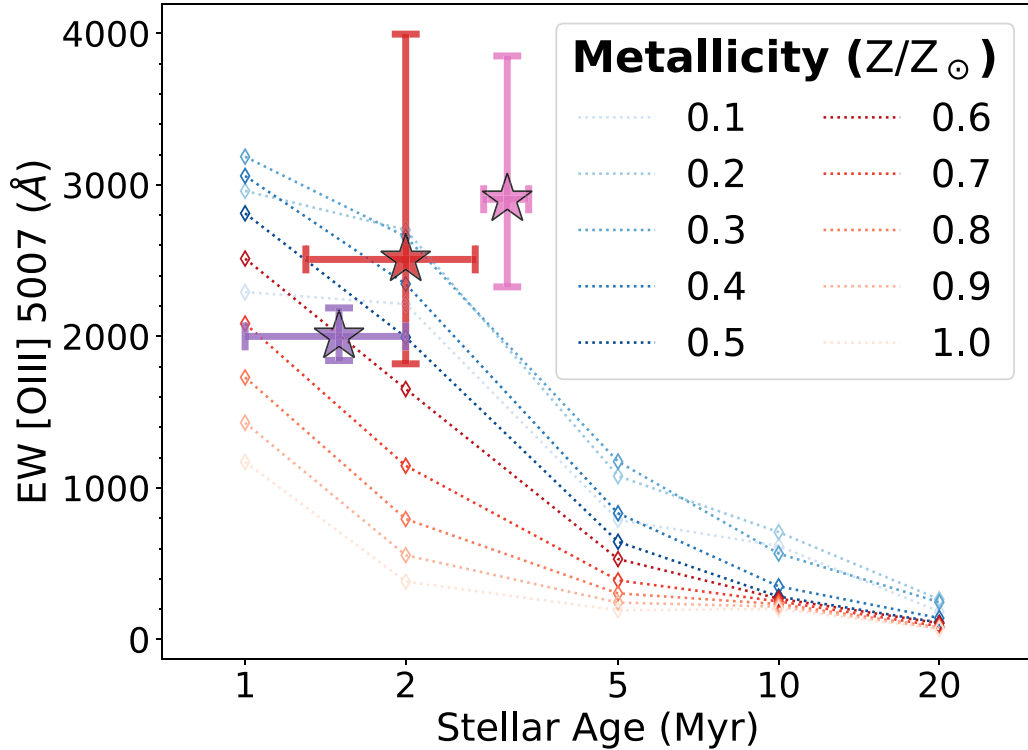


Figure 12. Relation between $\text{EW}[\text{O III}]$ and stellar population age for the BPASS binary model. Different colors represent various metallicity settings from 0.1 to 1 solar metallicity. The red, pink, and purple stars denote CEERS-3506, J1000+0211, and J0845-0123, respectively. $\text{EW}[\text{O III}]$ decreases as the stellar age increases. The relation between $\text{EW}[\text{O III}]$ and metallicity is not monotonic. Our results agree well with A. K. Inoue (2011).

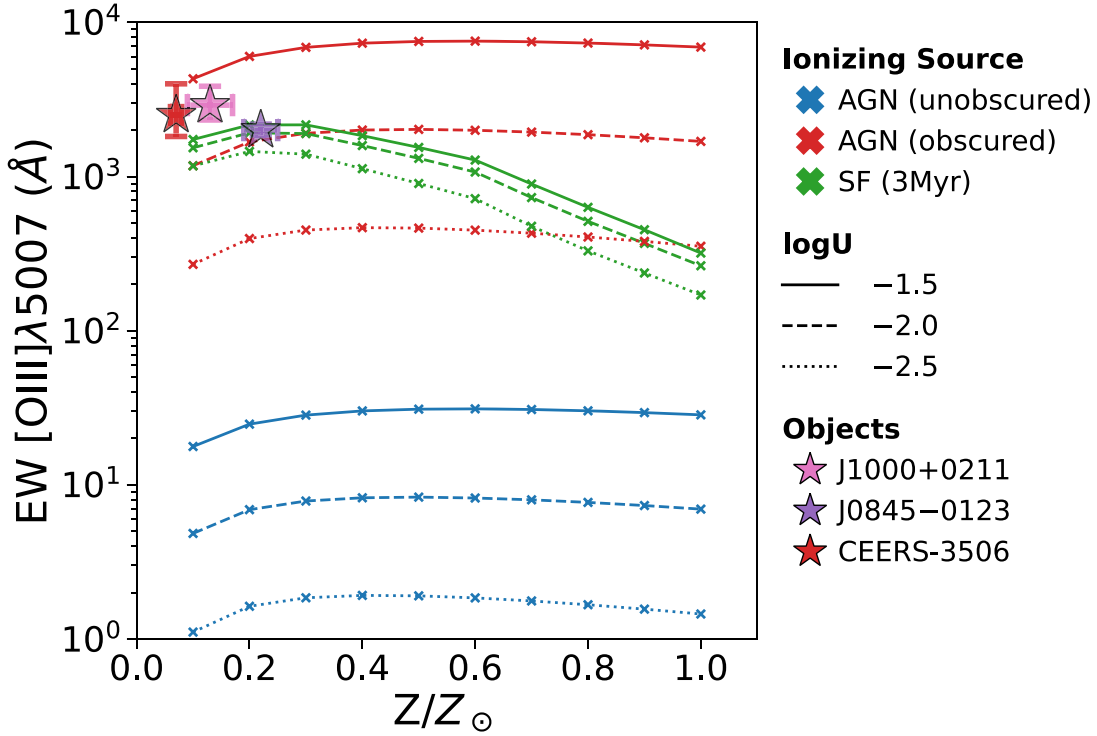


Figure 13. Relation between $\text{EW}([\text{O III}])$ and metallicity for different models. For clarity, we present our simulation results with representative parameters. The green, red, and blue lines denote the EWs for SF models of BPASS binary models at the stellar age of 3 Myr, obscured AGN, and unobscured AGN, respectively. The solid, dashed, and dotted lines denote the EWs for the ionizing parameter ($\log U$) of -1.5 , -2.0 , and -2.5 . The stars mark our objects.

AEGIS-X Deep survey, respectively. However, neither source is listed in the corresponding X-ray catalogs, with the absence of X-ray detection potentially indicating significant obscuration.

5. Summary

In this paper, we report the physical properties of three EELGs with strong $[\text{O III}]\lambda 5007$ emission lines. The pronounced EWs of their emission lines couple with a faint continuum, and thus necessitate sensitive observations for reliable detection of continuum emission. Below, we summarize our principal findings:

1. We present deep Subaru/FOCAS VPH850 spectra of the two most extreme $[\text{O III}]$ emitter candidates. We estimate $\text{EWs}([\text{O III}])$ with detected continua ($2000^{+188}_{-159}\text{\AA}$ for J0845–0123; $2905^{+946}_{-578}\text{\AA}$ for J1000+0211; Table 2). We find another extreme $[\text{O III}]$ emitter in the CEERS program with $\text{EW}([\text{O III}]) = 2508^{+1487}_{-689}\text{\AA}$.
2. Despite the absence of clear AGNs signatures from optical line diagnostics, our analysis reveals strong near-infrared excess in the SEDs of two of the galaxies, indicative of obscured AGNs activity. The detection of broad $\text{H}\alpha$, $\text{He I } \lambda 10830$, and $\text{Pa}\beta$ in CEERS-3506 further supports AGNs activity, allowing us to estimate black hole masses and explore the black hole to stellar mass relationship. Using various calibration methods, we estimate $\log(M_*/M_\odot) \sim 6.4\text{--}7.6$, corresponding to a black hole to stellar mass ratio of $M_*/M_* \sim 0.02\text{--}0.32$.
3. We measured the metallicity of the three objects with $Z \sim 0.07\text{--}0.20Z_\odot$ using the direct temperature method with $[\text{O III}] \lambda 4363$. To interpret our findings, we employ

Cloudy photoionization models, considering a range of parameters, including stellar and AGN incident spectra, metallicities, and ionization parameters. Our models indicate that the large $\text{EWs}([\text{O III}])$ cannot be fully explained by stellar or unobscured AGNs spectra alone, but are more consistent with the presence of obscured AGNs. The models successfully reproduce the observed $\text{EWs}([\text{O III}])$ by invoking a scenario where ionizing photons are efficiently produced by obscured AGNs with weak nuclear and stellar continua, matching the SED shapes.

4. We propose that, within the EELG population, particularly those with the most extreme $\text{EWs}([\text{O III}])$, the fraction of AGNs is likely higher than what optical line diagnostics suggest. However, larger sample sizes are needed to confirm this implication. This requires revisiting previously reported high- $\text{EW}([\text{O III}])$ emitters (e.g., blueberry galaxies from H. Yang et al. 2017, other $[\text{O III}]$ emitters from Y. Matsuoka et al. 2018, 2019) with JWST near-infrared and mid-infrared data.

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