On the Origin of the Strong Optical Variability of Emission-line Galaxies

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Abstract

Emission-line galaxies (ELGs) are crucial for understanding the formation and evolution of galaxies, while little is known about their variability. Here we report on the optical variability of a sample of ELGs selected in the COSMOS field, which has narrowband observations in two epochs separated by \( \gtrsim 12 \) yr. This sample was observed with the Suprime-Cam (SC) and Hyper Suprime-Cam (HSC) on the Subaru telescope in NB816 and \( i' / i \) bands, respectively. After carefully removing the wing effect of a narrowband filter, we check the optical variability in a sample of 181 spectroscopically confirmed ELGs. We find that 0 (0/68) \( \text{H} \alpha \) emitters, 11.9% (5/42) \( \text{O III} \) emitters, and 0 (0/71) \( \text{[O II]} \) emitters show significant variability (\( \Delta \alpha_{\text{NB}} \geq 0.20 \) mag) in the two-epoch narrowband observations. We investigate the presence of active galactic nuclei (AGN) in this variable ELG (var-ELG) sample with three methods, including X-ray luminosity, mid-infrared activity, and radio excess. We find zero bright AGN in this var-ELG sample but cannot rule out the contribution from faint AGN. We find that supernovae explosions (SNe) could also dominate the variability of the var-ELG sample. The merger morphology shown in the HST/F814W images of the entire var-ELG sample is in agreement with the enhancement of star formation, i.e., the SNe activity.

Unified Astronomy Thesaurus concepts: Emission line galaxies (459); Galaxies (573); Active galactic nuclei (16); Star formation (1569)

1. Introduction

Galaxies with strong emission lines in their spectra are known as emission-line galaxies (ELGs) and are typically less massive, less dusty, and more efficient in star formation than normal galaxies (e.g., Griffiths et al. 2021). Studying ELGs improves our understanding of the formation and evolution of distant galaxies, galaxy clusters, and cosmology. ELGs have been largely surveyed by various methods, e.g., spectroscopic surveys such as the Sloan Digital Sky Survey (SDSS; York & Adelman 2000), grism surveys (e.g., Momcheva et al. 2016), and narrowband (NB) imaging surveys (e.g., Geach et al. 2008; Sobral et al. 2015, and references therein). Among those methods, the NB imaging is the most efficient survey method for ELGs, as it covers the corresponding emission lines (e.g., \( \text{H} \alpha, \text{[O III]}, \text{[O II]} \) or \( \text{Ly} \alpha \)) of ELGs in a narrow redshift range.

In galaxies, the radiation of emission lines is mainly contributed by star formation, activities of central black holes, and shock excitation (see Kewley et al. 2019). Nebular emission lines, particularly \( \text{H} \alpha \), trace star formation rates (SFRs) in ELGs (Kennicut 1998), because the \( \text{H} \alpha \) emission is closely related to the photoionization driven by UV radiation from young and blue stars. Beside, other emission lines such as \( \text{[O III]} \) and \( \text{[O II]} \) can be SFRs indicators as well (see Madau & Dickinson 2014). The radiative shock driven by supernova would produce emission lines in the cooling of shock-heated gas (e.g., Cox 1972; Sutherland & Dopita 2017). Meanwhile, active galactic nuclei (AGN) often show strong emission lines in their spectra, which are marked as the evidence of central supermassive black holes (Krolik & McKee 1978; Ferland et al. 1979; Kallman & McCray 1982; also see Kewley et al. 2019).

In the past two decades, a large number of NB surveys search and study ELGs at various redshifts from \( z \approx 0 \) to 8 (Ouchi et al. 2020), which makes it possible to construct the star-forming history of the universe (e.g., see Madau & Dickinson 2014). For example, in the well-known COSMOS field (Scoville et al. 2007), ELGs from NB surveys provide clues to star formation in the redshift range from \( z \approx 0.05 \) to \( z \approx 1.47 \) (Geach et al. 2008; Hayashi et al. 2018). However, there is little work focusing on the optical variability of ELGs.

The optical variability of ELGs can be explained by three origins: (1) AGN activity. Variability is a basic phenomenon of AGN, which could be explained by various accretion disk and wind models (e.g., Ulrich et al. 1997; Choi et al. 2014; Heinis et al. 2016; Caplar et al. 2017; Cai et al. 2018; De Cicco et al. 2019). In addition, changing-look AGN could produce broad emission lines and high-ionization lines in several years (LaMassa et al. 2015). (2) Supernovae (SNe) explosions. SNe explosions would lighten the host galaxy in a timescale of months. Furthermore, the regions heated by SNe shocks significantly influence the radiation of emission lines, which evolve during the interaction between SNe and no-shock regions surrounded (see, e.g., Tartaglia et al. 2020). (3) Stellar
tidal disruption events (TDEs). TDEs in a gas-rich environment could produce strong Hα and [O III] emissions with no significant change in the continuum (Yang et al. 2013). So the question is, which process dominates the strong optical variability of ELGs?

The goal of this paper is to reveal the origin of the optical variability of ELGs. We use the NB and broadband (BB) imaging data taken in the COSMOS field in two epochs separated by $\geq 12$ yr to test the optical variability of ELGs. We then analyze the presence of AGN in the spectroscopically confirmed ELGs, which show variability in the NB data.

This paper is organized as follows. In Section 2 we introduce the sample selection of ELGs and the NB variability test method. The results of the variability test, the morphology, and the AGN fraction of our sample of strong variable ELGs are presented in Section 3. In Section 4 we discuss the AGN fraction in the whole ELG sample and possible origin of strong variability of our variable ELG sample. The result is concluded in Section 5. Throughout this paper, we assume the cosmological parameters of $H_0 = 70\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$.

2. The Sample of ELGs and the Variability Test Method

2.1. Data Description

The ELG sample in this work is selected with NB816 and BB imaging data in the COSMOS field taken with Suprime-Cam (SC; Miyazaki et al. 2002) and Hyper Suprime-Cam (HSC; Miyazaki et al. 2018) on the Subaru 8.2 m telescope. These NB816 images, observed with SC in 2004–2005 and HSC in 2016 and 2019, allow us to analyze the two-epoch NB variability of ELGs. The summary of the two-epoch observations is listed in Table 1. The processing flow on the sample selection of ELGs and the variability test is shown in Figure 1.

In 2004–2005 Subaru took an imaging survey with SC in the COSMOS field with panchromatic bands (Capak et al. 2007; Taniguchi et al. 2007) including NB816 and $i'$. These images are available from the IRSA\footnote{https://irsa.ipac.caltech.edu/} data server. SC worked in 2014–2017 in a shared-risk mode with HSC and was fully decommissioned in 2017.

Since 2014, Subaru had initiated the Hyper Suprime-Cam Subaru Strategic Survey Program (HSC-SSP; Aihara et al. 2018), which is a multiband imaging survey with wide, deep, and/or ultradepth exposures in many famous fields with its new imager HSC. The COSMOS field is covered by HSC-SSP deep and ultradepth surveys. The HSC $i$-band image used here, archived from HSC-SSP public data release 3 (PDR3; Aihara et al. 2022), is a combination of all observations taken from 2016 February to 2020 January.

2.2. Source Extraction and Photometry

We perform source extraction and photometry using SExtractor (Bertin & Arnouts 1996) in dual mode, which detect sources from the NB816 image and measure colors from the BB ($i/i'$) image (see Table 4 for the main SExtractor parameters). As the HSC NB816 band is deeper and with better image quality than the SC NB816 band (see Table 1), we choose HSC NB816 as the detection image. We also test the results with HSC $i$ as the detection image, which has little affection on the final result. As the automatic aperture magnitude MAG_AUTO is greatly affected by source blending and image seeing, we choose the fixed aperture magnitude rather than the automatic aperture magnitude in the following calculation. To check the seeing (point-source function) effect, fixed aperture magnitudes are derived in both 3″ and 6″ diameters. The NB variability tests with the two apertures have similar results, while a small fraction of ELGs show large uncertainties in their BB. This is because we choose the NB image as the detection image, so a larger aperture would cause more contamination of nearby objects in the deeper BB images. Therefore, we choose the aperture magnitude in a 3″ aperture in the following analysis.

As SExtractor would underestimate the photometric errors (see Bielby et al. 2012; Laigle et al. 2016), we correct for this effect by comparing the average $1\sigma$ error from faint (nonsaturated) objects detected by SExtractor and the standard deviation of fluxes obtained from empty background apertures. We randomly place $\sim40,000$ apertures with same 3″ diameters in the blank sky region to obtain the standard deviation of background fluctuations. Then the photometric errors from SExtractor are corrected by multiplying the ratio between the standard deviation of background fluctuations and the average $1\sigma$ error from SExtractor. The correction factors are $f_{\text{SC, } i'} = 1.9$, $f_{\text{SC, } i} = 1.7$, $f_{\text{HSC, } i'} = 3.2$, and $f_{\text{HSC, } NB} = 2.4$ for SC $i'$, SC NB816, HSC $i$, and HSC NB816, respectively. After this correction, the differences in the photometric errors between our catalog and the COSMOS2015 (Laigle et al. 2016) catalog for SC-selected ELGs in the SC BB and SC $i'$ bands are below 0.04 and 0.08 mag, respectively.

There are 1,187,790 sources detected in HSC NB816 band in the COSMOS field. After excluding saturated sources and bad areas marked in COSMOS2015 (Laigle et al. 2016), 653,524 sources are left. We then collect their aperture magnitudes in the HSC $i$, SC $i'$, and SC NB816 bands, for the following ELG selection and variability test. The photometric zero-point (ZP) is derived by a comparison of point-source photometry (3″ diameters) between our catalog and the COSMOS2015 catalog in the corresponding bands.

2.3. ELG Candidate Selection and Redshift Validation

We use the NB imaging technique to effectively select ELG candidates in each epoch. The selection criteria of the ELG candidates include a cut on the NB magnitude, a significant

| Table 1 |
| --- |
| Summary of the Two-epoch Broadband and Narrowband Observations with SC and HSC on the Subaru Telescope |
| | SC | HSC |
| **Observing Date** | | |
| 2004 | 2004–2005 | 2016–2020 | 2016, 2019 |
| **Filter** | $\lambda_c (\text{Å})$ | NB816 | $\Delta \lambda (\text{Å})$ | Depth (mag) | Saturation (mag) | Seeing (arcseconds) |
| $\lambda_c$ | 7641 | 8151 | 7711 | 8177 |
| $\Delta \lambda$ | 1497 | 117 | 1574 | 113 |
| Depth | 26.2 | 25.7 | 26.9 | 26.0 |
| Saturation | 20.0 | 16.9 | 18.6 | 16.8 |
| Seeing | $0.7$–1.2 | $0.7$–1.2 | 0.6–0.7 | 0.6–0.8 |

Notes. References of the observations: Taniguchi et al. (2007); Capak et al. (2007); Aihara et al. (2022); Hayashi et al. (2018).

a See Table 5 for details.
b Seeing values are FWHMs within $1\sigma$ errors of unsaturated point sources from the stacked images.
We then apply a color significance cut, $\Sigma \geq 3$, to exclude cases of false candidate ELGs caused by photometric scatters. The color significance $\Sigma$ is defined as:

$$\Sigma = \frac{BB - NB}{\sqrt{\sigma_{BB}^2 + \sigma_{NB}^2}},$$

(1)

where $\sigma_{NB}$ (BB and $\sigma_{BB}$) are the 3″ diameter aperture magnitudes and their errors in NB816 ($i' / i$ band), respectively.

An observed equivalent width ($EW_{\text{obs}}$) cut of 28 Å is applied to ensure that photons from galaxies in the NB filter are dominated by their emission line instead of their continuum. The emission-line flux $F_{\text{line}}$, continuum flux density $f_c$, and the $EW_{\text{obs}}$ of the emission line are defined as:

$$F_{\text{line}} = \frac{\Delta \lambda_{\text{NB}}}{1 - (\Delta \lambda_{\text{NB}}/\Delta \lambda_{\text{BB}})} \frac{f_{\text{NB}} - f_{\text{BB}}}{},$$

(2)

$$f_c = \frac{f_{\text{BB}} - f_{\text{NB}} (\Delta \lambda_{\text{NB}}/\Delta \lambda_{\text{BB}})}{1 - (\Delta \lambda_{\text{NB}}/\Delta \lambda_{\text{BB}})},$$

(3)

$$EW_{\text{obs}} = \frac{F_{\text{line}}}{f_c} = \frac{\Delta \lambda_{\text{NB}}}{f_{\text{BB}} - f_{\text{NB}} (\Delta \lambda_{\text{NB}}/\Delta \lambda_{\text{BB}})},$$

(4)

where $f_{\text{NB}}$ and $f_{\text{BB}}$ are the flux density in the NB and in the BB, respectively. We adopt the NB bandwidths ($\Delta \lambda_{\text{NB}}$) of 113 Å, and the broad bandwidth of ($\Delta \lambda_{\text{BB}}$) of 1574 Å. The corresponding criterion for $EW_{\text{obs}} > 28$ Å is (BB–NB) > 0.35 ($f_{\text{NB}}/f_{\text{BB}} > 1.38$) with assumptions of a flat continuum spectrum and a same central wavelength for NB and BB filters. However, because the central wavelength of the NB filter is redward from the center of the BB filter, nonflat continuum falling in the BB filter will have a color offset of (BB–NB). This color offset zero-point is calibrated as $\sim 0.1$ mag with the matched point sources, which show the continuum dominated in the BB and NB filters. Considering the color offset of 0.1 mag, we apply (BB–NB) $\geq 0.45$ mag in the sample selection (Figure 2). With the above three criteria, we select two ELG samples with Subaru-SC and Subaru-HSC, which contain 4975 and 6347 ELG candidates, respectively.

The enormous spectroscopic resources in the COSMOS field are used to validate the redshifts of ELG candidates. Spectroscopic redshifts are available in HSC-SSP public data release 3 (HSC-SSP PDR3), which includes several surveys such as zCOSMOS DR3 (Lilly et al. 2009), UDSz (Bradshaw et al. 2013; McLure et al. 2013), 3D-HST (Skelton et al. 2014; Momcheva et al. 2016), FOMOS-COSMOS (Silverman et al. 2015), NVDS (Le Fèvre et al. 2013), VIPERS PDR1 (Garilli et al. 2014), SDSS DR16 (Ahumada et al. 2020), SDSS QSO DR14 (Pâris et al. 2018), GAMA DR2 (Liske et al. 2015), WiggleZ DR1 (Drinkwater et al. 2010), DEEP2 DR4 (Davis et al. 2003; Newman et al. 2013), DEEP3 (Cooper et al. 2011, 2012), PRIMUS DR1 (Coil et al. 2011; Cool et al. 2013), 2dFGRS (Colless et al. 2003), 6dFGRS (Jones et al. 2004, 2009), C3R2 DR2 (Masters et al. 2017, 2019), DEIMOS 10k sample (Hasinger et al. 2018), LEGA-C DR2 (Straatman et al. 2018), and VANDELS DR1 (Pentericci et al. 2018). We then crossmatch the ELG candidate catalogs with these spectroscopic redshift catalogs with a match radius of 0″5. The matched samples include 647 and 648 sources from SC- and HSC-selected ELG candidates, respectively. Only 144 candidates are in both SC- and HSC-selected candidate ELG catalogs.

We then use spectroscopic redshifts to select true Hα, [O III], and [O II] emitters from ELG candidates (see Figure 3). The expected redshifts of Hα, [O III], and [O II] emitters are approximately 0.24, 0.63, and 1.19 for the NB816-selected ELGs, respectively. Figure 3 presents the redshift distribution of ELG candidates selected with the NB816 and $i$ bands. By checking the profiles of the two NB816 filters, we constrain the observed wavelength of ELGs’ emission lines $\lambda_{\text{obs}}$ within 8127–8205 Å to rule out the wing effect of the NB filter (see Section 2.4 in detail). Therefore, the corresponding redshift ranges are $0.238 < z < 0.250$, $0.623 < z < 0.639$, and $1.181 < z < 1.202$ for Hα, [O III], and [O II] emitters, respectively (also listed in Table 2). Only $\sim 16\%$ (27%) of 647 (648) SC-selected (HSC-selected) candidate ELGs are confirmed as the true sample of Hα, [O III], and [O II] ELGs by their spectroscopic redshifts. Most of the remaining candidates are actually Balmer-break galaxies or 4000 Å break galaxies located in the redshift range of 0.7–1.1 (see Figure 3, the gray histograms for the distributions of spectroscopic redshifts). We should address that with extra criteria, such as the photometric range and/or BB color–color selection, the contamination fraction in the ELG candidates would be significantly decreased (e.g.,
In this work, as we need the accurate redshift information, we choose to match the spectroscopic catalogs directly and do not need to worry about the contamination.

The spectroscopically confirmed ELGs selected with SC and HSC are then merged together with TOPCAT (Taylor 2005) as the final ELG sample. In a total number of 181 ELGs, 93 are selected in both SC and HSC, 8 are selected in SC only, and 80 are selected in HSC only. Sorted by their redshifts, we obtain 26 Hα, 33 [O III], and 42 [O II] emitters selected in SC, and 67 Hα, 36 [O III], and 70 [O II] emitters selected in HSC. Finally, the combined ELG sample includes 68 Hα, 42 [O III], and 71 [O II] emitters (see also Table 2).

2.4. Optical Variability Test

As the SC and HSC observations with the NB816 and i band are separated by \( \geq 12 \) yr, we check ELGs’ two-epoch variation in the NB816 (\( \Delta m_{\text{NB816}} \equiv \text{NB816}_{\text{HSC}} - \text{NB816}_{\text{SC}} \)) and i band (\( \Delta m_i \equiv i_{\text{HSC}} - i'_{\text{SC}} \)), respectively.

There is an anticorrelation between \( \Delta m_{\text{NB816}} \) and the emission lines’ central wavelength \( \lambda_{\text{obs}} \) (see the top panel of Figure 4). This is because the transmission profiles of NB816 filters with HSC and SC are slightly different; therefore the NB flux is sensitive to ELGs with emission lines centered at the wings of the NB filter (see Figure 4). We then correct the NB magnitude by subtracting a term of \( 2.5 \log (1/I_{\lambda_{\text{obs}}}) \); here \( I_{\lambda_{\text{obs}}} \) is the transmitted fraction of the filter curve at \( \lambda_{\text{obs}} \). The corrected NB magnitudes (NB816\(_{\text{corrected,HSC}}\) and NB816\(_{\text{corrected,SC}}\)) are used in the following analysis of optical variability.

The \( \Delta m_{\text{NB816}} \) distribution as a function of the emission lines’ central wavelength before and after the NB correction are presented in the top panel and middle panel of Figure 4, respectively. Obviously, in the central wavelength region overlapped by the two NB filters, the anticorrelation between \( \Delta m_{\text{NB816}} \) and \( \lambda_{\text{obs}} \) is corrected. We therefore select the spectroscopically confirmed ELG sample with emission lines...
located in this wavelength range (from 8127 to 8205 Å; see the shaded region in Figure 4) in the following optical variability test.

We then check the variability of ELGs selected from an individual epoch and both epochs (i.e., selected by both HSC and SC). Figure 5 shows the NB-magnitude difference versus the BB-magnitude difference for these cases. For all cases, the BB-magnitude differences \( \Delta m \) distribute around 0 mag and show no significant systematic bias (\( \langle \Delta m \rangle = 0.005 \pm 0.018 \)). However, unlike the distribution of \( \Delta m \), the distributions of NB-magnitude differences \( \Delta m_{\text{NB816}} \) are significant before and after the NB correction, especially for those ELGs selected by either HSC or SC. After the NB correction, the distribution of \( \Delta m_{\text{NB816}} \) shows no systematic offset (\( \langle \Delta m_{\text{NB816}} \rangle = -0.007 \pm 0.086 \)).

There are 102 out of 181 ELGs with \( \Delta m_{\text{NB816}} \leq 0 \). The ratio of numbers of ELGs brightened and dimmed is approximately 5.6:4.4. This unequal fraction may be due to the detection image chosen here, which is HSC NB816 and is deeper than SC NB816. Brightened sources are more easily detected in HSC NB816.

### 3. Results

#### 3.1. Presence of Strong Optical Variability in ELGs

The variability test of ELGs in this work is presented in Figure 6. Obviously, the variability in the NB is more significant than that in the BB, which may indicate strong variable emission lines in these ELGs. However, we should point out that the observing strategies of the NB and BB are different, which prevent us to check if the variability in the NB is caused by the variable emission lines or by the short-term variable continuum.

We then select the strong variable ELGs (hereafter, var-ELGs) in this sample. The selection methods are summarized as below. First, the variability should be significant at \( S/N > 5 \). Then the rms of the two-epoch NB variation of AGN in our ELG sample, selected via four techniques discussed in Sections 3.2 and 4.1, is calculated as \( \sigma(\Delta m_{\text{NB816}}) = 0.067 \) mag. We therefore choose a two-epoch variation cut of \( \Delta m_{\text{NB816}} \geq 0.20 \) mag to select the ELGs with strong variability, corresponding to a search for outliers at the \( \geq 3\sigma \) level compared to typical AGN in this ELG sample. Only 5 [O III] emitters of 181 ELGs meet this criterion, corresponding to a fraction of 2.8% (0, 11.9%, and 0 for \( \text{H} \alpha \), [O III], and [O II] emitters, respectively) of this ELG sample.

#### 3.2. Presence of AGN in Variable ELGs

Variability is one of the basic observational features of AGN. To investigate the presence of AGN in this ELG sample, we apply three methods, including X-ray photometry, mid-infrared (MIR) color, and radio activity. In addition, we also apply the emission-line diagnostic in a subsample of \( \text{H} \alpha \) emitters. X-ray emission indicates the contribution from the accretion of the central massive black hole. The MIR color presents the radiation of the dust torus of AGN. Radio activity directly traces the radio jet, which is also powered by the accretion system around the central massive black hole. The emission-line diagnostic (e.g., the Baldwin–Phillips–Terlevich (BPT) diagram; Baldwin et al. 1981) can effectively classify star-forming galaxies and AGN by the hardness of radiation. Therefore, these four methods would help effectively select AGN in a galaxy sample.

Thanks to the abundant multiband photometric and spectroscopic survey data existing in the COSMOS field, we would use these different methods to reveal AGN in our ELG sample, especially the var-ELG sample. First, we use X-ray data observed with the Chandra space telescope to identify AGN in the COSMOS field. Next, we search for AGN by using MIR data taken with the Spitzer Space Telescope in this field. We then crossmatch our ELG catalog with the COSMOS Very Large Array (VLA) 3 GHz AGN catalog to select radio-active AGN. Lastly, we measure the fluxes of \( \text{H} \alpha, \text{H}\beta, \text{[N II]} \lambda 6583, \text{and [O III]} \lambda 5007 \) lines from available spectra taken from the zCOSMOS DR3 and plot the BPT diagram for identifying AGN from \( \text{H} \alpha \) ELGs.

#### 3.2.1. X-Ray Luminosity

The Chandra COSMOS-Legacy Survey (Civano et al. 2016) is an X-ray survey in the 2.2 deg\(^2\) COSMOS field taken with the ACIS instrument on the Chandra space telescope. The Chandra COSMOS-Legacy survey covers the soft (0.5–2.0 keV), hard (2.0–10.0 keV), and full (0.5–10 keV) bands. In the full band, Chandra COSMOS-Legacy detects 4016 sources with a detection limit of \( 8.9 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \). There is also the XMM-Newton COSMOS (XMM-COSMOS;
Galaxies with X-ray luminosities \(L_{\text{FB}}^{\text{full band}}\) of \(10^{42} \text{ erg s}^{-1}\) are commonly regarded as AGN (see, e.g., Szokoly et al. 2004; Finkelstein et al. 2009). The detection limit of the Chandra COSMOS-Legacy survey can be converted to X-ray luminosity limits of \(L_{\text{FB}}^{\text{H}\alpha} = 10^{41.2} \text{ erg s}^{-1}\) for \(\text{H}\alpha\) emitters \((z \sim 0.25)\), \(L_{\text{FB}}^{[\text{O III}]} = 10^{42.2} \text{ erg s}^{-1}\) for \([\text{O III}]\) emitters \((z \sim 0.62)\),

Cappelluti et al. 2007; Hasinger et al. 2007) in this field with the flux limit of \(3.3 \times 10^{-15} \text{ erg cm}^{-2} \text{s}^{-1}\) in 2–10 keV band.

Figure 4. Top panel: observed central wavelengths of ELGs’ emission lines \(\lambda_{\text{obs}}\) vs. \(\Delta m_{\text{NB816}}\) before NB correction. Middle panel: \(\lambda_{\text{obs}}\) vs. \(\Delta m_{\text{NB816}}\) after NB correction. Bottom panel: distribution of \(\lambda_{\text{obs}}\) for \(\text{H}\alpha\), [O III], and [O II] emitters. The light blue regions mark the wavelength range of 8127–8205 Å, which is used to select ELGs as the final ELG sample for the variability test. The red dashed lines show the variability cut of ~0.2 mag. ELGs selected by HSC and SC are marked in open circles and open triangles, respectively. Var-ELGs are marked in solid symbols. AGN selected via X-ray, mid-infrared, radio-excess, and emission-line diagnostic methods are marked in stars. The colors shown here are consistent with those in Figure 3. The transmission curves of the SC NB816 (gray solid line) and the HSC NB816 (black solid line) filters are also overlapped in these figures to display the fake variable effect caused by the wing of an NB filter.
and $L_{\text{FB}} = 10^{12.9} \text{ erg s}^{-1}$ for [O II] emitters ($z \sim 1.19$), implying that all X-ray AGN in H$\alpha$ emitters, and bright X-ray AGN in [O III] and [O II] emitters should be selected with the current X-ray survey in the COSMOS field.

By checking the footprint of the X-ray surveys, we find that all of five var-ELGs are covered by Chandra and XMM-Newton, but none of them show X-ray detection. Therefore, in the X-ray view, bright AGN are unlikely the origin of var-ELGs.

### 3.2.2. Mid-infrared Activity

The Spitzer COSMOS survey (S-COSMOS; Sanders et al. 2007) is a four-channel (3.6, 4.5, 5.8, and 8.0 $\mu$m) MIR survey in the COSMOS field taken with the Infrared Array Camera (IRAC) on the Spitzer space telescope. The observations taken in 2006 January covered the full COSMOS field. The 5$\sigma$ detection limits of the MIR survey are 0.9, 1.67, 11.3, and 14.6 $\mu$Jy in the 3.6, 4.5, 5.8, and 8.0 $\mu$m bands, respectively.

All var-ELGs are covered by the S-COSMOS survey. We apply the MIR AGN selection criteria following Stern et al. (2005). The result is shown in Figure 7 and Table 3. Only four var-ELGs have $\gtrsim 5\sigma$ detections in all the four MIR bands, while none is selected as MIR AGN. The remaining var-ELG has nondetection in all MIR bands, implying weak MIR activities. Therefore, we conclude that no MIR AGN is found in our variable ELG sample.

#### 3.2.3. Radio Excess

Delvecchio et al. (2017) surveyed 7700 radio sources in the COSMOS field with the VLA as the VLA-COSMOS 3 GHz Large Project. They presented an AGN catalog including 1169 sources brighter than the 5$\sigma$ sensitivities of 2.3 $\mu$Jy beam$^{-1}$ in 3 GHz, along with 1.4 GHz detection (Schinnerer et al. 2010). To investigate the presence of AGN, they performed a variety of methods including spectral energy distribution fitting, X-ray luminosity, MIR activity, and radio excess. The X-ray and MIR methods they used are similar to what we used in this paper. As for the radio method, they assume that the 1.4 GHz radio excess to the star formation rate indicates the activity of AGN in the host galaxy.

By checking the footprint of the VLA-COSMOS 3 GHz and 1.4 GHz surveys, respectively, we find that all of the var-ELGs are covered. However, none of them is matched with this AGN catalog within a 1.5$\sigma$ radius, indicating no strong radio activity in var-ELGs.

#### 3.2.4. Emission-line Diagnostic

The spectroscopic redshifts of our ELG sample are collected from the zCOSMOS DR3, 3D-HST, RIMUS, C3R2, and DEIMOS surveys (see Section 2.3 for the detailed references). Due to the different kinds of observational limits (e.g., the wavelength coverage and the exposure depth) of various spectroscopic surveys, only a subsample of ELGs can be probed via the emission-line diagnostic systematically. Among these surveys, the zCOSMOS survey has a relatively better spectral quality and a larger coverage for our ELG sample. The zCOSMOS-bright survey releases $\sim 10,000$ galaxies’ spectra in the redshift range of $0.1 < z < 1.2$. A total of 73 spectra from this survey are available for the ELG sample ($\sim 40\%$ of our ELG sample). As the wavelength coverage of these spectra is in the range of $5550–9450$ Å, the BPT diagram analysis is limited to the galaxies at redshifts lower than $\sim 0.4$. Therefore, we only analyze the available spectra of 42 H$\alpha$ emitters here.

We first measure the fluxes of emission lines including H$\alpha$, H$\beta$, [N II] $\lambda 6583$, and [O III] $\lambda 5007$ (see Figure 8 for examples). The line-flux errors are estimated by computing the rms in the corresponding continuum region nearby the emission lines. We then plot the ratios of [N II] $\lambda 6583$/H$\alpha$ versus [O III] $\lambda 5007$/H$\beta$ (the BPT diagram; Baldwin et al. 1981; Kewley et al. 2006) in Figure 9. We identify 2 AGN via the BPT diagram from 42 H$\alpha$ emitters. The final results are given in Table 2. We note that this emission-line diagnostic is not applied to the var-ELG sample because their [N II] $\lambda 6583$ and H$\alpha$ lines are not covered by the wavelength range of their spectroscopic surveys.
3.2.5. Final Classification

As shown in Tables 2 and 3, none of the var-ELGs is identified as AGN via X-ray luminosity, MIR activity, or radio-excess methods. This result indicates that strong variability in ELGs is not dominated by AGN. However, we should note that faint AGN would be missed in our var-ELG sample with these three methods when considering their detection limits.

3.3. Morphology

We use HST/ACS F814W imaging data to check the morphology of var-ELGs. Their morphology in NB816 and $i(i')$ with SC and HSC are also checked. Figure 10 shows the image cutouts of var-ELGs, including the NB816 and $i(i')$ images with HSC(SC), and HST/F814W images.

With HST, all of the var-ELGs show the structures of mergers (var-ELG 1, 3, 4, and 5) or post-mergers (var-ELG 2), indicating star-forming activities. Sorted by their identifications, the separations of these galaxy pairs are $\lesssim 0''27-0''45$, corresponding to physical sizes of $\lesssim 1.8$–3.2 kpc.

4. Discussion

4.1. Fractions of AGN

We have applied three methods, including X-ray luminosity, MIR activity, and radio excess to identify AGN among var-ELGs in Section 3. We also apply the BPT diagnostic to a subsample of H$\alpha$ emitters. Combining these four methods, we find 17 AGN in the total 181 ELGs (see Table 2 and Figures 7 and 9 for details). The total AGN fractions are $\sim 4.4\%$, 0%, and 19.7% for H$\alpha$ emitters at $z \sim 0.24$, [O III] emitters at 0.63, and [O II] emitters at 1.19, respectively. These AGN are marked with stars in Figures 4 and 6.

To check if our spectroscopically confirmed ELG sample is biased on AGN selection, we compare the X-ray AGN fraction in our sample to that in previous works. For consistency, the criterion for X-ray AGN is set to full-band (0.5–10 keV) X-ray luminosity $L_{FB} \lesssim 10^{43}$ erg s$^{-1}$ (Martini et al. 2013; see Table 2). The evolution of the X-ray AGN fraction from $z = 0.25$ to 3.09 is presented in Figure 11. The AGN fractions at $z = 0.25$, 0.75 and 1.25 were computed by Martini et al. (2013) and other previous works (e.g., Lehmer et al. 2009; Martini et al. 2009; Digby-North et al. 2010; Haines et al. 2012) from galaxy clusters. The AGN fraction at $z = 2.30$ and 3.09 were measured in galaxy protoclusters (Lehmer et al. 2009; Digby-North et al. 2010; also see Martini et al. 2013). In our ELG sample, we find zero X-ray AGN for either H$\alpha$ emitters or [O III] emitters, and five X-ray AGN for [O II] emitters. We then estimate the AGN fractions of $< 2.7\%$, $< 4.4\%$, and $7.0^{+4.6}_{-3.0}\%$ for ELGs at $z \sim 0.24$, 0.63, and 1.19, respectively. Errors and 1$\sigma$ upper limits of fractions are calculated following Gehrels (1986). The X-ray AGN fractions in our sample are consistent with those in previous works.

As given in Section 3, the fraction of variable sources in ELGs ($\sim 2.8\%$) is several times lower than the fraction of AGN in ELGs. Furthermore, none of the var-ELGs has been
## Table 3
Physical Parameters of Variable ELGs

| Var-ID   | Line   | R.A.      | Decl.      | Corrected HSC NB816 (mag) | HSC _i_ (mag) | Corrected SC NB816 (mag) | SC _i_ (mag) | Δ_mNB816 (mag) | X-ray AGN | MIR AGN | Radio AGN | AGN | spec-z | SFR_{spec^a} (M_\odot yr^{-1}) | SFR_{em} (M_\odot yr^{-1}) |
|----------|--------|-----------|------------|---------------------------|--------------|--------------------------|--------------|----------------|----------|---------|-----------|-----|--------|-----------------------------|---------------------------|
| var-ELG1 | [O III] | 150.547364 | 2.804791   | 21.799 ± 0.020            | 21.949 ± 0.006| 21.421 ± 0.027          | 21.941 ± 0.034| 0.378 ± 0.033 | 0        | 0       | 0         | 0   | 0.623  | 0.14                        | 1.71                      |
| var-ELG2 | [O III] | 150.268059 | 2.775813   | 21.282 ± 0.010            | 21.677 ± 0.004| 21.008 ± 0.022          | 21.659 ± 0.030| 0.275 ± 0.024 | 0        | 0       | 0         | 0   | 0.623  | 1.46                        | 3.18                      |
| var-ELG3 | [O III] | 150.067333 | 2.473629   | 23.544 ± 0.071            | 23.623 ± 0.023| 22.720 ± 0.067          | 23.643 ± 0.080| 0.825 ± 0.097 | 0        | 0       | 0         | 0   | 0.636  | −0.03                       | 0.95                      |
| var-ELG4 | [O III] | 150.681233 | 2.763416   | 20.968 ± 0.010            | 21.610 ± 0.005| 20.743 ± 0.022          | 21.608 ± 0.031| 0.225 ± 0.024 | 0        | 0       | 0         | 0   | 0.636  | 3.46                        | 5.54                      |
| var-ELG5 | [O III] | 149.936369 | 1.990318   | 21.827 ± 0.016            | 22.504 ± 0.008| 21.582 ± 0.036          | 22.511 ± 0.045| 0.245 ± 0.039 | 0        | 0       | 0         | 0   | 0.637  | 1.65                        | 2.72                      |

**Note.** Column (1): ID of variable ELGs in this paper. Column (2): emission-line type. Columns (3)–(4): coordinates (equatorial). Columns (5)–(7): corrected NB816 magnitude with HSC and SC as described in Section 2.4. Columns (6)–(8): BB magnitude with HSC and SC. Column (9): NB816-magnitude differences between NB816 observations with HSC and SC. Columns (10)–(12): X-ray-, MIR-, and radio-selected AGN. 0 means nondetection. Column (13): total number of AGN via the above three methods. Column (14): spectroscopic redshift. Columns (15)–(16): two-epoch SFRs of variable ELGs calculated by SFR-emission-line indicators.

* SFR([O III]) following Zhuang & Ho (2019).
identified as AGN through X-ray luminosity, MIR activity, or radio excess. This infers that bright AGN are unlikely the main origin of the variability of our var-ELG sample. However, due to the detection limits of various methods, we cannot rule out the contribution from faint AGN in these var-ELGs.

### 4.2. Stellar-driven Variability?

After excluding bright AGN as the origin of var-ELGs, we check the possibility of stellar-driven variable events, such as SNe and TDEs. The variability caused by the extra flux of such event, as well as its event rate, is discussed here. Note that, as the observations in the NB and BB of this sample lack coherence (Table 5), below we assume that the variability in the NB is caused by the short-term variable continuum caught in either epoch of NB observation.

It is critical to determine whether the extra fluxes yielded by SNe and TDEs are significant enough to provide the $\geq 0.20$ mag variability for ELGs at $z = 0.63$. For type Ia SNe (SNe Ia) with typical peak absolute magnitudes of $M_B \sim -19.3$ mag (Branch 1998), the extra flux it can contribute is $\sim 4 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ at $z = 0.63$ by assuming a flat spectrum. The specific values of magnitude differences caused by SNe

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**Figure 8.** Examples of measurement of $\text{H} \beta$, $[\text{O III}]$, $\text{H} \alpha$, and $[\text{N II}]$ emission lines derived from the zCOSMOS spectra. The integrating regions of each emission lines are marked in blue and green shadows.
explosions are then estimated from the apparent magnitudes of the host galaxies. For instance, in galaxies with apparent magnitudes of $21$ (or $23.5$) mag, the SNe having a peak $M_R \sim -19.3$ mag will result in variations of $\sim -0.10$ (or $-0.72$) mag at $z \sim 0.63$. While by considering the absolute magnitudes of type II SNe (SNe II), which ranges from $-17$ up to $-22$ mag at peak (Kiewe et al. 2012; Taddia et al. 2013; Reynolds et al. 2020; Tartaglia et al. 2020), type II SNe can produce the magnitude variation up to $-0.82$ (or $-2.72$) mag for galaxies with magnitudes of $21$ (or $23.5$) mag at $z \sim 0.63$.

With the above estimations, the supernovae (SNe) Ia hypothesis can only explain the variability of var-ELG3, which changed from $23.5$ to $22.7$ in the two-epoch NB observations required an event with the absolute magnitude of $\geq -19.3$ mag. The remaining four var-ELGs had the NB magnitudes in the range of $20.7$–$21.8$ with two-epoch NB-magnitude differences of $0.22$–$0.38$, requiring events with absolute magnitudes of $\geq -19.5$–$20.3$ mag. These values of the magnitudes and two-epoch magnitude differences are in agreement with the hypothesis of SNe II driven variability. However, the required transients would be extreme SNe II events at the bright end, which could be quite rare. Overall, the above estimations imply that luminous SNe II would bring in the strong variability of our var-ELGs, while we could not rule out the contribution from faint AGN or other luminous transient events, e.g., the ultraluminous fast blue optical transient (FBOT) reported recently by Jiang et al. (2022).

Event rates of these stellar-driven transients are also very helpful for us to understand the origin of variable ELGs. We check the event rate of two types of SNe, type Ia SNe, and core-collapse SNe, respectively. As our sample is a subkind of galaxies selected with their strong emission lines at the corresponding redshifts, we estimate the number of SNe per galaxy per year ($R_{SN}$), defined as:

$$R_{SN} = SNR \times M_{SM}.$$  

Here the SNR is the SNe rate per unit mass in units of yr$^{-1} M_{\odot}^{-1}$, and $M_{SM}$ are the stellar masses of galaxies in units of $M_{\odot}$. According to the SNe rate–size relation for SNe Ia and SNe II/Ibc galaxies (Li et al. 2011), the SNe rate per unit mass could be described as:

$$\log \left( \frac{SNR(SNe Ia)}{10^{52}} \right) = -0.50 \times \log \left( \frac{M_{SM}}{10^{10}} \right) - 0.65,$$

$$\log \left( \frac{SNR(SNe II/Ibc)}{10^{52}} \right) = -0.55 \times \log \left( \frac{M_{SM}}{10^{10}} \right) - 0.073. \quad (6)$$

We adopt a median stellar mass ($10^{9.35} M_{\odot}$) of our ELGs as the typical mass of ELGs. Thus we can derive the SNe event rate ($R_{SN}$) of our ELG sample as: $0.46 \times 10^{-12} M_{\odot}^{-1}$ yr$^{-1}$ for SNe Ia, and $1.88 \times 10^{-12} M_{\odot}^{-1}$ yr$^{-1}$ for SNe II or SNe Ibc, corresponding to a total event rate (SNe Ia + SNe II + SNe Ibc) of $\sim 0.01$ yr$^{-1}$. With the estimations above, there are $\sim 1.8$ SNe expected in the ELG sample (in total 181 ELGs) per year. This estimated event rate of SNe is $\sim 2.8$ times lower than the fraction of var-ELGs in the ELG sample. However, the SN rates used here are measured in the local university (Li et al. 2011), while our ELGs have redshifts of $\geq 0.24$. Furthermore, the SN rate may be higher in the our var-ELG sample, because of their strong interactions between galaxies (see Section 4.3 for details). With the above discussion, SNe may play an important role in contributing to the variability of var-ELGs.

TDEs would turn the disrupted star into the extra fuel to the active/inactive accretion disk possessed by the central supermassive black hole of the host galaxy. According to Gezari et al. (2009), the TDE flare could be as energetic as $\sim 1.6 \times 10^{43}$ erg cm$^{-2}$ s$^{-1}$ at $z \sim 0.19$. The corresponding extra fluxes could be $\sim 1 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ at $z = 0.63$. With the similar estimation above, the magnitude variations caused by TDEs could also introduce the magnitude differences of our ELG sample. However, compared to event rates of SNe, the TDE rate is much lower, expected a few times $10^{-5}$ per galaxy per year (see Gezari 2021; corresponding to $\sim 2 \times 10^{-5}$ var-ELGs per year for our ELGs sample). Overall, SNe are more likely to be the origin of strong optical variability than TDEs in our ELG sample.

4.3. The Merging Features of Var-ELGs

As described in Section 3.3, all var-ELGs show merging or post-merged structures. Their angle separations of galaxy pairs are less than $0.75$, corresponding to projected separations of $\leq 3.4$ kpc. These kind structures may imply an underlying correlation between the very close galaxy–galaxy interaction and variability of ELGs.

Several works had pointed out that the interaction between galaxies can significantly enhance the AGN and star-forming activity (e.g., Kennicutt & Keel 1984; Alonso et al. 2007). As shown by the results given in Sections 3.2 and 4.1, none of the bright AGN are found in the var-ELG sample, indicating that bright AGN are not the main origin of the strong variability of our var-ELGs. However, we could not rule out the contribution from faint AGN.

Observations of SDSS galaxy pairs had shown that the smaller the projected separation, the stronger the enhancement of star formation (Li et al. 2008; Patton et al. 2013), especially in less massive galaxies (Li et al. 2008). This is consistent with the result given in Section 3.3. As all var-ELGs have small projected separations ($\leq 3.4$ kpc) and low masses ($\leq 10^{10} M_{\odot}$), they are more likely to have higher enhancements in star formation. This is in agreement with the picture of SN-driven variability.
5. Conclusion

We use two-epoch NB imaging, separated by $\gtrsim 12$ yr, to check the strong optical variability of a sample of 181 spectroscopically confirmed ELGs in the COSMOS field. The two-epoch NB imaging was observed with the HSC and SC instruments of the Subaru telescope. This sample includes 68 H$\alpha$, 42 $[\text{O III}]$, and 71 $[\text{O II}]$ emitters at redshifts $z \sim 0.24$, 0.63, and 1.19, respectively. Only five $[\text{O III}]$ emitters show significant variability in the NB [(\$\Delta m_{\text{NB}}$) $\gtrsim 3$ $\sigma_{\Delta m_{\text{NB,AGN}}}$ = 0.20 mag]. The fractions of var-ELGs are 2.8% of the whole ELG sample.

We probe the existence of AGN in this ELG sample via X-ray luminosity, mid-infrared activities, and radio excess. We also apply the emission-line diagnostic in a subsample of H$\alpha$ emitters. We find no bright AGN in the var-ELG sample, indicating that the strong optical variability of our ELGs is not dominated by bright AGN. However, we cannot rule out the contribution from faint AGN.

We discuss the possibility of SNe contributing to the strong variability of var-ELGs. This strong variability could be qualitatively explained by the luminous SNe.

With HST images, we find that all of the var-ELGs have merging or post-merged features with projected separations of $\lesssim 3.4$ kpc. The strong interaction between galaxies may indicate enhanced star formation activity.
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Facilities: COSMOS, Subaru(HSC and SC), IRSA, HST (ACS), Chandra, Spitzer, VLA.

Software: astropy (Astropy Collaboration et al. 2013, 2018), Source Extractor (Bertin & Arnouts 1996), SWarp (Bertin 2010), TOPCAT (Taylor 2005).

Appendix

Extra Tables

The main SExtractor parameters are shown as Table 4. The observation dates of NB and BB with SC and HSC are listed in Table 5.

| Parameter | Value |
|-----------|-------|
| DETECT_TYPE | CCD |
| DETECT_MINAREA | 5 |
| DETECT_MAXAREA | 100,000 |
| DETECT_THRESH | 0.6 (in sigma) |
| ANALYSIS_THRESH | 0.6 (in sigma) |
| FILTER | Y |
| FILTER_NAME | Gauss_2.5_5x5.conv |
| DEBLEND_NTHRESH | 64 |
| DEBLEND_MINCONT | 0.00001 |
| CLEAN | Y |
| CLEAN_PARAM | 1 |
| PHOT_APERTURES | 17.65, 2.94, 11.76, 35 |
| PHOT_AUTOPARAMS | 2.5, 3.5 |
| PHOT_PETROPARAMS | 2.0, 3.5 |
| PHOT_AUTOAPERS | 0.0, 0.0 |
| PHOT_FLUXFRAC | 0.2, 0.5, 0.8 |
| SATUR_LEVEL | 50,000 |
| SATUR_KEY | SATURATE |
| MAG_ZEROPoint | SC NB816 31.07 |
| MAG_GAMMA | 4 |
| MAG_GAMMA | 0 |
| GAIN | GAIN |
| PIXEL_SCALE | 0.17 |
| SEEING_FWHM | SC NB816 0.95 |
| BACK_TYP | AUTO |
| BACK_VALUE | 0 |
| BACK_SIZE | 128 |
| BACK_FILTERSIZE | 3 |
| BACKPHOTO_TYPE | LOCAL |
| BACKPHOTO_THICK | 30 |
| Filter | SC | HSC |
|-------|----|-----|
| i'i | 2020 Jan | |
| | 2019 May | |
| | 2017 Apr | |
| | 2017 Mar | |
| | 2004 Feb | |
| | 2004 Jan | |
| | 2017 Feb | |
| | 2017 Jan | |
| | 2016 Dec | |
| | 2016 Nov | |
| | 2016 Feb | |

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