Finding of a Population of Active Galactic Nuclei Showing a Significant Luminosity Decline in the Past $\sim 10^3$–$10^4$ yr

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Abstract

Recent observations have revealed an interesting active galactic nucleus (AGN) subclass that shows strong activity at large scales ($\sim 1$ kpc) but weaker at small scales ($< 10$ pc), suggesting a strong change in the mass accretion rate of the central engine in the past $10^3$–$10^4$ yr. We systematically search for such declining or fading AGNs by cross-matching the Sloan Digital Sky Survey type 1 AGN catalog at $z < 0.4$, covering the [O III] $\lambda$5007 emission line, which is a tracer for the narrow-line region emission, with the Wide-field Infrared Survey Explorer (WISE) mid-infrared (MIR) catalog covering the emissions from the dusty tori. Out of the 7653 sources, we found 57 AGNs whose bolometric luminosities estimated from the MIR band are at least one order of magnitude fainter than those estimated from the [O III] $\lambda$5007 emission line. This luminosity-declining AGN candidate population shows four important properties: (1) the past AGN activity estimated from the [O III] $\lambda$5007 line reaches approximately the Eddington limit; (2) more than 30% of the luminosity-declining AGN candidates show a large absolute variability of $\Delta W1 > 0.45$ mag in the previous $\sim 10$ yr at the WISE 3.4 $\mu$m band; (3) the median ratio of $\log ([\text{N II}] \lambda 6584/\text{H}$ $\alpha \lambda 6563) = -0.52$, suggesting a lower gas metallicity and/or higher ionization parameter compared to other AGN populations; and (4) the second-epoch spectra of the population indicate a spectral type change for 15% of the sources. This population provides insights on the possible connection between the luminosity decline that started $\sim 10^3$–$10^4$ yr ago and the decline in the recent 10 yr.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); Quasars (1319); Galaxies (573)

Supporting material: machine-readable table

1. Introduction

One big question in astronomy is how supermassive black holes (SMBHs) increase their mass across the cosmic epoch in the universe. Active galactic nuclei (AGNs) are a key population for SMBH growth since they are in a rapidly growing state of their BH masses through the gas accretion to the central SMBHs, until they reach the redshift-independent maximum mass limit at $M_{\text{max}} \sim$ a few $\times 10^{10}$ $M_\odot$ (Netzer 2003; Kormendy & Ho 2013). This indicates that SMBHs and their accretion systems might have a self-regulating process that shuts down the growth of SMBHs before reaching a certain maximum mass ($\leq M_{\text{max}}$; Natarajan & Treister 2009; Inayoshi & Haiman 2016; King 2016).

One of the biggest unknowns for this accretion process is how long such an AGN phase lasts. Several studies indicate that the total lifetime of the AGN is $\sim 10^7$–$10^9$ yr (Soltan 1982; Marconi et al. 2004), and even the single episode has a length of $> 10^5$ yr (Schawinski et al. 2015) and likely around $10^6$–$10^7$ yr (Marconi et al. 2004; Hopkins et al. 2006), which is still orders of magnitude longer than one person’s lifetime of $\sim 10^2$ yr.

One way to expand the AGN variability window beyond the human lifetime is to compare the activity of the different physical scales of the AGN, as the shutdown process propagates from the inner regions to the outer ones with the light-crossing time (see, e.g., Ichikawa & Tazaki 2017). AGN have multiple indicators with different physical scales from 10 to 100 $R_\odot$ (X-ray-emitting corona and UV-optically bright accretion disk, AD; Dai et al. 2010; Morgan et al. 2010). 0.1–10 pc (the mid-infrared bright tori; Burtscher et al. 2013), to $10^3$–$10^4$ pc (narrow-line region, NLR; Bennett et al. 2002). Using those AGN components with different physical scales enables us to explore the long-term luminosity variability on the order of $\sim 10^3$–$10^4$ yr. Recent studies have revealed that there are certain populations of AGNs with strong activity in large scales but weaker ones in the small scales, which suggests a strong decline of the accretion rate into the central SMBHs. These AGNs are called fading or dying AGNs. Recently >30 such fading AGN candidates have been reported (Schirmer et al. 2013; Ichikawa et al. 2016; Kawamuro et al. 2017; Keel et al. 2017; Sartori et al. 2018; Villar-Martín et al. 2018; Wylezalek et al. 2018; Ichikawa et al. 2019a, 2019b; Chen et al. 2019, 2020a, 2020b; Esparza-Arredondo et al. 2020; Saade et al. 2022; Finlez et al. 2022).

In this paper, we conduct a systematic search of such luminosity-declining AGNs by combining the Sloan Digital Sky Survey (SDSS) AGN catalog with the Wide-field Infrared Survey Explorer (WISE) MIR all-sky survey. The SDSS AGN catalog of Mullaney et al. (2013) contains 25,670 AGNs with the [O III] $\lambda$5007 emission line, which is one of the large-scale AGN indicators with $\sim$kiloparsec scale. WISE enables us to obtain the warm dust emission heated by AGNs, which is one of the small physical scale AGN indicators with $\sim$1 pc scale.
obtain the long-term AGN variability timescale of $\sim10^3$–$10^4$ yr. Throughout this paper, we adopt the same cosmological parameters as Mullaney et al. (2013): $H_0 = 71\text{ km s}^{-1}\text{ Mpc}^{-1}$, $\Omega_M = 0.27$, and $\Omega_\Lambda = 0.73$.

2. Sample and Selection

2.1. SDSS Type 1 AGNs of Mullaney et al. (2013)

Our initial parent sample starts from the AGN catalog compiled by Mullaney et al. (2013), which includes 25,670 optically selected AGNs from the SDSS DR7 data release (Abazajian et al. 2009) at $z < 0.4$, where $H_0$ is within the SDSS wavelength coverage. Mullaney et al. (2013) conducted their own spectral fitting of the SDSS spectra including the narrow components of the narrow H$\beta$ and H$\alpha$ emission lines, which gives better fitting results for the emission lines compared to the original SDSS fitting method, which applied a more simplified fitting (e.g., York et al. 2000; Abazajian et al. 2009).

In this study, we used only type 1 AGNs from the Mullaney et al. (2013) catalog in searching for luminosity-declining AGNs for two reasons: (1) the more reliable observed [O III] $\lambda$5007 luminosities with small extinctions considering their viewing angle (e.g., Antonucci 1993), and (2) availability of $M_{\text{BH}}$ measurements thanks to the existence of the broad emission lines. Mullaney et al. (2013) classified AGNs as type 1 if they fulfill the following criteria for their H$\alpha$ line: (1) an extra Gaussian (for the broad component) in addition to the narrow Gaussian provides a significantly better fit, (2) the broad component flux exceeds the narrow one, and (3) the FWHM of the broad H$\alpha$ component is $>600\text{ km s}^{-1}$. The obtained type 1 AGN catalog contains 9455 sources and provides the emission-line fluxes, redshifts, and luminosities of [O III] $\lambda$5007, H$\alpha$, H$\beta$, and [N II] $\lambda$6584, and the obtained fluxes are separated into narrow and broad components, as well as the physical values based on those emission-line measurements, such as BH masses ($M_{\text{BH}}$) and Eddington ratio ($\lambda_{\text{Edd}}$), both of which are estimated based on the broad H$\alpha$ emission lines (Greene & Ho 2005).

We then limited our sample to the sources with reliable spectral fitting. First, we limit our samples to low extinction values for the NLR with $A_V < 10$, since otherwise the luminosities of these sources are unrealistically overestimated (see Mullaney et al. 2013, for more details). This reduces the sample to 9372 sources. Second, we limit the sources whose [O III] $\lambda$5007 emission line is significantly detected, with a signal-to-noise ratio (S/N) $\geq 5$. The resulting type 1 AGN sample contains 7755 sources.

It should be pointed out that searching only for type 1 luminosity-declining AGNs significantly reduces the possibility for finding genuine “dying” AGNs whose central engine is completely quenched, such as Arp 187 (Ichikawa et al. 2019a, 2019c), which is likely classified as a type 2 AGN in the optical spectra because of the lack of broad emission lines already in the current SDSS spectra. We will explore a luminosity-declining/dying type 2 AGN systematic search in a forthcoming paper.

2.2. Cross-matching with WISE

The WISE mission mapped the entire sky in 3.4 $\mu$m (W1), 4.6 $\mu$m (W2), 12 $\mu$m (W3), and 22 $\mu$m (W4) bands (Wright 2010a; Wright et al. 2010). In this study, we obtained the data from the latest ALLWISE catalog (Cutri et al. 2013). We used the pipeline-measured magnitudes at the W3 band based on the point-spread function profile fitting on $\sim6''$ scale, called profile fitting magnitude and $\text{w3mpro}$ in the WISE catalog terminology. The positional accuracy based on cross-matching with the Two Micron All Sky Survey catalog is $\sim2''$ at the $3\sigma$ level (see, e.g., Ichikawa et al. 2012, 2017), and we also applied the $2''$ cross-matching radius between the SDSS optical coordinates and WISE. This reduces the sample from 7755 to 7723 sources.

We obtained the W3-band fluxes and treated the value as a detection for the sources with $\text{ph\_qual} = A, B, C$, with S/N higher than 2. The $\text{ph\_qual} = U$ were treated as an upper limit detection since we are looking for low-luminosity AGNs in the MIR band, and it is therefore also important to consider the weak detections in the MIR bands for our parent sample. We also applied the contamination-free sources with $\text{ccflag} = 0$. This reduces the sample to 7653, where 6028/1496/75/54 of the sources have the photometric quality of $\text{ph\_qual} = A/B/C/U$, respectively. We refer to this sample as the “parent sample” for searching the luminosity-declining AGNs.

2.3. AGN Luminosities and Bolometric Corrections

We measured the AGN bolometric luminosities based on the obtained AGN indicators tracing different physical scales. For the NLR luminosities tracing a $\sim10^3$–$10^4$ pc scale, we utilized the observed [O III] $\lambda$5007 luminosities obtained by Mullaney et al. (2013) and then applied the constant bolometric correction of $L_{\text{bol, [O III]}} = 3500L_{\lambda5007}$ with the median error of 0.38 dex (e.g., Heckman et al. 2004). We note that our sample contains [O III] luminous AGNs that are not covered in Heckman et al. (2004), notably the sources with $L_{\lambda5007} \gtrsim 10^{42} \text{ erg s}^{-1}$. We here apply the same constant bolometric correction even for those sources since the overall spectral shape does not change in the standard disk regime even when the accretion rate changes (Kato et al. 2008). One might also wonder whether the bolometric correction might change in the super-Eddington regime. We will discuss this point later in Section 3.2. Another point is that Mullaney et al. (2013) already provide the bolometric luminosities of the sample by utilizing the extinction-corrected [O III] $\lambda$5007 luminosities. However, we did not use those since they are often unrealistically large values exceeding $L_{\text{bol, [O III]}} > 10^{48} \text{ erg s}^{-1}$, which is the Eddington limit of the mass of $M_{\text{BH}} \sim 10^{10} M_\odot$, the known maximum mass limit of the SMBHs.

For the AGN dust luminosities tracing $\sim10$ pc scale, we first derived the rest-frame 15 $\mu$m luminosities by applying the k-correctation from the obtained WISE 12 $\mu$m flux density. The rest-frame 15 $\mu$m flux density was extrapolated from the obtained observed 12 $\mu$m flux density with the assumption of the AGN IR spectral template of Mullaney et al. (2011) and with the obtained redshift. The AGN bolometric luminosities from the AGN dust were finally estimated from the bolometric correction curve by Hopkins et al. (2007), which has a typical bolometric correction value of $L_{\text{bol, 15\mu m}} \sim 10L_{\lambda5007}$ with a scatter of a factor of 2.

In addition, we also measured the bolometric AGN luminosities from the AD emission by using the rest-frame B-band continuum fluxes, tracing $\sim100R_g$ scale assuming the
standard thin-disk accretion (e.g., Kato et al. 2008). The B-band fluxes were calculated from the continuum of the SDSS spectra by Mullaney et al. (2013) and assumed that the continuum is dominated by the AGN AD. For the bolometric correction, we applied the one by Hopkins et al. (2007).

In summary, we obtained the three AGN bolometric luminosities from the NLR, AGN dusty torus, and AD.

Figure 1 shows the bolometric luminosity correlation between the one from the NLR and the one from the AGN dusty torus, showing a rough 1:1 relation.

2.4. The Emission Region Size of Each AGN Indicator

We estimate the emitting size of each AGN component by utilizing either theoretical or empirical luminosity–distance relations. The emitting size from the SMBH to the B band in the optical can be obtained by the standard geometrically thin α-disk (e.g., Kato et al. 2008), and it is expressed as

$$D_{\text{AD}}/\text{au} = 886.3 \left(\frac{\lambda}{4450 \, \text{Å}}\right)^{4/3} \left(\frac{M_{\text{BH}}}{10^8 \, M_\odot}\right)^{1/3} \left(\frac{L_{\lambda, \text{bol}}}{10^{46} \, \text{erg s}^{-1}}\right)^{1/3},$$

(1)

where we assume the radiation efficiency $\eta_{\text{rad}} = 0.1$ (Soltan 1982) and $\lambda = 4450$ Å (B band) as a tracer of the AD (Malkan & Sargent 1982).

The size of the MIR dust emission region heated by AGNs is obtained by MIR high spatial resolution interferometry observations (e.g., Kishimoto et al. 2011) and can be written as

$$D_{\text{torus}}/\text{kpc} = 1.3 \left(\frac{L_{\text{bol}, 15\mu m}}{10^{46} \, \text{erg s}^{-1}}\right)^{0.01}.$$  

(2)

The size of the NLR and its AGN luminosity dependence has been studied by several authors (Bennert et al. 2002; Hainline et al. 2013; Husemann et al. 2014). Here we apply the relation between the NLR size and the AGN luminosity by Bae et al. (2017) because they utilized the observed [O III] $\lambda 5007$ luminosities as a tracer of AGN luminosity, which is suitable for our sample of type 1 AGNs.

$$D_{\text{NLR}}/\text{kpc} = 2.4 \left(\frac{L_{\text{bol}, \text{[OIII]}}/\text{obs}}{10^{46} \, \text{erg s}^{-1}}\right)^{0.41}.$$  

(3)

The median size of the NLR of our parent sample is $D_{\text{NLR}} \sim 1$ kpc, which is consistent with our assumption that the NLR is a tracer of the past AGN activity of $10^3$–$10^4$ yr.

2.5. Selection of Luminosity-declining AGN Candidates

In order to search for luminosity-declining AGN candidates, it is necessary to compare two AGN indicators, a large-scale indicator and a short-scale indicator. The NLR is a promising tool as a large-scale AGN indicator because of its large size with $\sim 1$–$10$ kpc, and the [O III] $\lambda 5007$ emission line is one of the good indicators of NLR luminosity (Bennert et al. 2002). On the other hand, the emission from the dusty tori is a good AGN indicator tracing a smaller physical scale of $\sim 10$ pc (Jaffe et al. 2004; Puckham et al. 2005; Radomski et al. 2008; Raban et al. 2009; Ramos Almeida et al. 2009; Alonso-Herrero et al. 2011; Höning et al. 2012; Burtscher et al. 2013, 2013; Höning et al. 2013; Tristram et al. 2014; Ichikawa et al. 2015; Ichikawa et al. 2016; Ichikawa & Tazaki 2017; Ichikawa et al. 2019a, 2019c), and the location of J0916a (orange upper bound), which is a fading AGN whose fading phase is likely recently started (<$10^2$ yr) with strong past outburst activity in the NLR (Chen et al. 2019, 2020a, 2020b). The selection criteria of the luminosity-declining AGN candidates discussed in Section 2.5 are represented by the red dashed line.

Figure 1. The correlation of the bolometric AGN luminosity estimated from the WISE 12 $\mu$m band and [O III] $\lambda 5007$ emission line. The gray circles represent the parent sample, and the blue filled circles represent the luminosity-declining AGN candidates. The orange dashed line represents the 1:1 line of the two luminosities. For the comparison with other fading/dying AGNs, we showed the location of Arp 187 (blue upper bound), which is one of the most promising dying AGNs (Ichikawa et al. 2016; Ichikawa & Tazaki 2017; Ichikawa et al. 2019a, 2019c), and the location of J0916a (orange upper bound), which is a fading AGN whose fading phase is likely recently started (<$10^2$ yr) with strong past outburst activity in the NLR (Chen et al. 2019, 2020a, 2020b).
López-Gonzaga et al. 2016; Lopez-Rodriguez et al. 2018) and can be traced by the MIR luminosities (e.g., Gandhi et al. 2009; Ichikawa et al. 2012, 2017, 2019b; Nikutta et al. 2021a, 2021b).

Figure 1 shows the luminosity correlation between the two AGN bolometric luminosities from different AGN indicators, the NLR (~kpc) and dusty tori (~10 pc), considered to be tracing the past AGN activities of ~3000 and ~30 yr ago (Ichikawa & Tazaki 2017). Figure 1 shows a 1:1 relation for most of the sample, while some sources have a significantly smaller value at $L_{\text{bol}, \lambda 5007}/L_{\text{bol}, [O \text{III}]} < 0.1$, shown with blue circles below the red dashed line.

Figure 2 shows the histogram of the logarithmic ratio $\log(R)$, defined as

$$\log(R) = \log \left( \frac{L_{\text{bol}, \lambda 5007}}{L_{\text{bol}, [O \text{III}]} } \right).$$

Here we used the Scott function (Scott 1979) to define the optimal bin width. We conducted one Gaussian fitting of the histogram of $\log(R)$, and all three parameters (amplitude, mean, and standard deviation) were set as free. The fitting still leaves an excess of the distribution at $\log(R) \sim -1$, indicating an additional component, which is also suggested from the blue point sources in Figure 1. We then applied the two-Gaussian fitting with all parameters set as free, and the second Gaussian component nicely reproduces the second peak at $\log(R) \sim -0.7$.

We also checked the reduced $\chi^2$ values of the fittings, with $\chi^2 = 3.5$ for two Gaussians and $\chi^2 = 5.4$ for one Gaussian fitting. This indicates that the distribution can be well described with at least two Gaussian components as shown in Figure 2, and it also suggests that there is a significant peak at $\log(R) \sim -0.7$, which might be related to a population of luminosity-declining AGN candidates in this study.

Based on the histogram shown in Figure 2, we selected AGNs with $\log(R) < -1$, and we refer to them as “luminosity-declining AGN candidates” hereafter. As shown in Figure 1, our selection cut is much more conservative considering the location of another reported fading AGN, SDSS J0916a, in the plane, which has likely started luminosity decline in the past $<10^2$ yr (Chen et al. 2020b). On the other hand, most of our sample spans $-1.5 < \log(R) < -1$, which is one order of magnitude larger than that of Arp 187, which is a dying AGN, whose central engine is completely quenched. This is also a natural outcome considering that our sample is type 1 AGNs whose broad-line region still exists, even if they might be in a luminosity-declining phase.

As a result, 57 luminosity-declining AGN candidates were selected, which is ~0.7% of the parent sample. Table 1 summarizes the list of the physical parameters of the luminosity-declining AGN candidates in this study.

3. Results

3.1. Basic Sample Properties

We here summarize the BH properties of the obtained 57 luminosity-declining AGN candidates. First, we show the basic differences between the luminosity-declining AGN candidates and the parent sample. Then, we show the properties of luminosity-declining AGN candidates on the SMBH activities.

3.1.1. AGN Luminosity and Redshift Plane

Figure 3 shows the redshift distributions as a function of $L_{\text{bol}, [O \text{III}]}$ and $L_{\text{bol}, \lambda 5007}$ for the luminosity-declining AGN candidates (blue filled circles) and the parent sample (gray circles). Figure 3 shows two important things. One is that the median $L_{\text{bol}, \lambda 5007}$ of luminosity-declining AGN candidates are almost similar to that of the parent sample, while the median $L_{\text{bol}, [O \text{III}]}$ is one order of magnitude higher than that of the parent sample. This indicates that our luminosity-declining AGN candidates had a very luminous AGN phase in the past, and we will discuss this later in Section 4.1.

The second is that our luminosity-declining AGN candidates are slightly biased to higher redshift at $z > 0.2$. This is partly due to the combination of our selection criteria for selecting large $L_{\text{bol}, [O \text{III}]} \lambda 5007$ luminosities with $L_{\text{bol}, [O \text{III}]} > 10^{45}$ erg s$^{-1}$ as shown in Figure 1, and such sources are a dominant population only at $z > 0.2$ as shown in the left panel of Figure 3. Actually, 77% of the luminosity-declining AGN candidates are located in a redshift $> 0.2$, which is a higher fraction compared to the parent sample (62%). This is also suggested from the difference in the redshift distribution of the two populations (luminosity-declining AGN candidates and parent sample), showing the $p$-value of 0.03, suggesting that redshift distribution is slightly skewed to higher redshift for our luminosity-declining AGN candidates, and the $p$-value becomes 0.08 if we limit our sample only to sources with $z > 0.2$, which suggests a nonsignificant difference in the distribution (Greenland et al. 2016).

3.1.2. BH Mass and Bolometric Luminosity Distributions

The BH mass ($M_{\text{BH}}$), one key measurement obtained from the SDSS spectra, is also compiled for all of our samples using the broad H$\alpha$ emission lines (Greene & Ho 2005), through the spectral fitting done by Mullaney et al. (2013).7

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7 The equation of Greene & Ho (2005) allows a maximum limit of reddening of E(B−V)~0.12 by following Cardelli et al. (1989). The extinction-corrected [O III] $\lambda 5007$ luminosities sometimes reach unrealistically high [O III] $\lambda 5007$ luminosities for some AGNs. This is a reason why we apply the observed broad H$\alpha$ luminosity in this study. Note that using the extinction-corrected broad H$\alpha$ luminosity (Domínguez et al. 2013; Calzetti et al. 2000) for estimating the $M_{\text{BH}}$ would not change our main results because such a sample with unrealistically high AGN luminosity is not a dominant population.
Table 1

| Column | Header Name | Unit | Description |
|--------|-------------|------|-------------|
| 1      | OBJID       |      | SDSS DR7 Object ID |
| 2      | zspec       |      | Spectroscopic Redshift |
| 3      | RAdeg       | deg  | Right ascension |
| 4      | Decl        | deg  | Declination   |
| 5      | SMBH-MASS   | 10^9 M_☉ | Solar mass (M_☉) in units of M_☉ |
| 6      | e_SMBH-MASS | 10^6 M_☉ | Error of solar mass (ΔM_☉) in units of M_☉ |
| 7      | F-12um      | 10^-17 erg s^-1 cm^-2 | 12 μm band flux in units of erg s^-1 cm^-2 |
| 8      | e-F-12um    | 10^-17 erg s^-1 cm^-2 | Error of 12 μm band flux in units of erg s^-1 cm^-2 |
| 9      | L-12um      | erg s^-1 | 12 μm band luminosity (L_{12um}) in units of erg s^-1 |
| 10     | e-L-12um    | erg s^-1 | Error of 12 μm band luminosity (ΔL_{12um}) in units of erg s^-1 |
| 11     | L-15um-BOLO | erg s^-1 | 15 μm band bolometric luminosity (L_{bol,15um}) in units of erg s^-1 |
| 12     | e-L-15um-BOLO | erg s^-1 | Error of 15 μm band bolometric luminosity (ΔL_{bol,15um}) in units of erg s^-1 |
| 13     | PH-QUAL-12um|      | Photometric quality for the 12 μm band (A:S/N > 10 & B:S/N > 3 & C:S/N > 2) |
| 14     | F-NII       | 10^-17 erg s^-1 cm^-2 | [N II] λ6584 flux (F_{NII}) in units of erg s^-1 cm^-2 |
| 15     | e_F-NII     | 10^-17 erg s^-1 cm^-2 | Error of [N II] λ6584 flux (ΔF_{NII}) in units of erg s^-1 cm^-2 |
| 16     | L-NII       | erg s^-1 | [N II] λ6584 luminosity (L_{NII}) in units of erg s^-1 |
| 17     | L-NII       | erg s^-1 | Error of [N II] λ6584 luminosity (ΔL_{NII}) in units of erg s^-1 |
| 18     | F-HA        | 10^-17 erg s^-1 cm^-2 | Hα flux (F_{Hα}) in units of erg s^-1 cm^-2 |
| 19     | e_F-HA      | 10^-17 erg s^-1 cm^-2 | Error of Hα flux (ΔF_{Hα}) in units of erg s^-1 cm^-2 |
| 20     | L-HA        | erg s^-1 | Hα luminosity (L_{Hα}) in units of erg s^-1 |
| 21     | e_L-HA      | erg s^-1 | Error of Hα luminosity (ΔL_{Hα}) in units of erg s^-1 |
| 22     | F-O III     | 10^-17 erg s^-1 cm^-2 | [O III] λ5007 flux (F_{O III}) in units of erg s^-1 cm^-2 |
| 23     | e_F-O III   | 10^-17 erg s^-1 cm^-2 | Error of [O III] λ5007 flux (ΔF_{O III}) in units of erg s^-1 cm^-2 |
| 24     | L-O III     | erg s^-1 | [O III] λ5007 luminosity (L_{O III}) in units of erg s^-1 |
| 25     | e_L-O III   | erg s^-1 | Error of [O III] λ5007 luminosity (ΔL_{O III}) in units of erg s^-1 |
| 26     | L-OIII-BOLO | erg s^-1 | [O III] λ5007 bolometric luminosity (L_{bol,O III}) in units of erg s^-1 |
| 27     | L-O-III-BOLO | erg s^-1 | Error of [O III] λ5007 bolometric luminosity (ΔL_{bol,O III}) in units of erg s^-1 |
| 28     | F-HB        | 10^-17 erg s^-1 cm^-2 | Hβ flux (F_{Hβ}) in units of erg s^-1 cm^-2 |
| 29     | e_F-HB      | 10^-17 erg s^-1 cm^-2 | Error of Hβ flux (ΔF_{Hβ}) in units of erg s^-1 cm^-2 |
| 30     | L-HB        | erg s^-1 | Hβ luminosity (L_{Hβ}) in units of erg s^-1 |
| 31     | e_L-HB      | erg s^-1 | Error of Hβ luminosity (ΔL_{Hβ}) in units of erg s^-1 |
| 32     | F-OPTICAL   | 10^-17 erg s^-1 cm^-2 | B-band flux (F_{B-band}) in units of erg s^-1 cm^-2 |
| 33     | L-OPTICAL   | erg s^-1 | B-band luminosity (L_{B-band}) in units of erg s^-1 |
| 34     | SIZE-NLR    | pc   | Emitting size of the NLR (D_{NLR}) |
| 35     | SIZE-TORUS  | pc   | Emitting size of the dusty torus (D_{torus}) |
| 36     | SIZE-AD     | pc   | Emitting size of the accretion disk (D_{ad}) |
| 37     | EDD-NLR     |      | λ_{edd} estimated for the NLR out of the [O III] λ5007 line information |
| 38     | EDD-TORUS   |      | λ_{edd} estimated for the torus out of the MIR photometric information |
| 39     | EDD-AD      |      | λ_{edd} estimated for the accretion disk out of the optical photometric information |
| 40     | LOG-R       |      | log(R) |
| 41     | DELTA-W1    | mag  | WISE W1 variability (ΔW1) |
| 42     | MID-WISE    | days | MJD of the WISE observation |
| 43     | MID-SDSS    | days | MJD of the SDSS observation |

Note. Table 1 is published in its entirety in the machine-readable format. All column names, their units, and descriptions are shown here for guidance regarding its form and content.

(This table is available in its entirety in machine-readable form.)

Both the population of luminosity-declining AGN candidates and the parent sample have similar median BH masses of (log(M_{BH}/M_☉)) = 8.0 ± 0.5 (for luminosity-declining AGN candidates) and (log(M_{BH}/M_☉)) = 7.8 ± 0.5 (for the parent sample). This suggests that our selection does not show a statistically significant difference on the BH mass as also seen in Figure 4.

3.2. AGN Light Curves in the Past ~10^4 yr

One of our goals is to obtain how rapidly luminosity-declining AGN candidates have experienced the luminosity decline in the past ~3 × 10^3 yr. To investigate this long-term AGN variability, we estimate the Eddington ratio (λ_{edd} = L_{bol}/L_{edd}), where L_{edd} is Eddington luminosity and L_{edd} ~ 1.26 × 10^8 (M_{BH}/M_☉) erg s^-1 of our sample. Considering that a few bolometric luminosities are estimated based on the different AGN indicators tracing different physical scales as discussed in Section 2.4, we estimate the Eddington ratio for each AGN indicator.

Figure 5 shows the time evolution of the average Eddington ratio for the luminosity-declining AGN candidates and the parent sample in the past ~3 × 10^3 yr. The look-back time (t_{lookback}) was calculated based on the light-crossing time of the three AGN indicators with different physical scales of AD, dusty tori, and NLR (see Section 2.4). We also take into
account the different observation dates for the WISE and SDSS observations, and we chose 2022 February 2 (or MJD = 59612) as our reference time ($t_{\text{lookback}} = 0$). The average MJD of the WISE observation is 55335/55325 for the luminosity-declining AGN candidates/parent sample, and the average one of the SDSS DR7 is 52997/53046. As a result of the different observation epochs between the WISE and SDSS DR7, the average $t_{\text{lookback}}$ for the AD and dusty tori is almost the same value as shown in Figure 5.

Figure 5 indicates two important things for our luminosity-declining AGN candidates and the parent sample. One is that our parent sample shows on average the constant Eddington ratio over the entire time range, that is, the previous $\sim 3 \times 10^3$ yr, indicating that the intrinsic variability should be on average smaller than the scatter of $\sim 0.4$ dex. This scatter value is consistent with previously known variability strength of typical AGNs in the timescale of $\sim 10$ yr (e.g., Hook et al. 1994; Sesar et al. 2007; Kozłowski et al. 2010; MacLeod et al. 2010), and our results suggest that the stochastic variabilities could be within the scatter of 0.4 dex even for the longer timescale of $\sim 10^3$ to $10^4$ yr. This long-term stability of AGN luminosity over the timescale of $\sim 10^3$ to $10^4$ yr is partially suggested from the relation between the X-ray and [O III] $\lambda 5007$ luminosity correlations of AGNs in the local universe, which shows a correlation with the scatter of $\sigma \sim 0.4$ dex (Panessa et al. 2006; Berney et al. 2015; Ueda et al. 2015).

The second is that luminosity-declining AGN candidates show a large luminosity decline between the [O III] $\lambda 5007$ emission region and the torus one, that is, in the previous $\sim 10^5$ to $10^4$ yr. This is a natural outcome since we set the ratio cut of $R < 0.1$. A more interesting trend of the light curve for luminosity-declining AGN candidates is that previous AGN luminosities traced by the [O III] $\lambda 5007$ emission region have reached almost the Eddington limit with $\log \lambda_{\text{Edd}} \sim 0$, while the current Eddington ratio is similar to that of the parent sample. This indicates that our fading AGN selection applied for type 1 AGNs turns out to be an efficient way to find AGNs that experienced the past AGN burst reaching the Eddington limit, and this is partially suggested from Figure 3 and Section 3.1.1.

One might wonder whether the bolometric correction for the [O III] $\lambda 5007$ line might not have the same values between the standard disk and super-Eddington phase accretion. Although there are no studies on the bolometric corrections including super-Eddington phase, our luminosity-declining AGN candidates (and also the parent type 1 AGN sample) do not contain extremely super-Eddington sources reaching $\lambda_{\text{Edd}} > 1$, with the maximum value of $\lambda_{\text{Edd}} \sim 4$ in the NLR. This means that even if the bolometric correction is not constant in the super-Eddington phase, the maximum difference is up to a factor of 4, and the difference is likely smaller for most of the super-Eddington sources. Therefore, the constant bolometric correction used in this study does not strongly affect the main results in this study.

One might also wonder whether all Eddington limit or super-Eddington sources in the [O III] $\lambda 5007$ emitting region might also have a similar trend of the AGNs declining in luminosity as seen in the luminosity-declining AGN candidates. To check this, we also selected [O III] $\lambda 5007$ bright AGNs that are defined as $\lambda_{\text{Edd}} > 0.5$ based on the [O III] $\lambda 5007$ AGN bolometric luminosities. This luminosity cut selects the sources with the average value of $\lambda_{\text{Edd}} = 0.8$, which is almost consistent with the one of luminosity-declining AGNs of $\lambda_{\text{Edd}} = 0.7$. The green crosses in Figure 5 show the one for [O III] $\lambda 5007$ bright AGNs, and they certainly show a slight luminosity decline in the past $10^3$ to $10^4$ yr, while the luminosity decline is smaller than that of luminosity-declining AGN candidates. This suggests that higher Eddington sources have a shorter lifetime residing in such a high Eddington ratio phase compared to the one in the lower
and scatter of the three look-back times were calculated based on the averaged emitting size of the ADs, dusty tori, and the NLRs. Here the dashed lines and gray area represent the median decline reaching a factor of \( > 10 \) in the timescale of \( 10^3 - 10^4 \) yr.

3.3. IR Variability Tracing the Past \( \sim 10 \) yr

It is worthwhile to trace the IR luminosity variability from the dusty torus by using the ALLWISE and NEOWISE IR light curves of W1 and W2 bands covering the past 10 yr (Mainzer 2014; Mainzer et al. 2014), and they are suitable bands for tracing the relatively inner part of the AGN dusty torus emission (e.g., Mateos et al. 2012; Stern et al. 2012; Assef et al. 2018). The ALLWISE database provides the WISE All-Sky catalog, the WISE 3-Band Cryo catalog, and the WISE Post Cryo catalog, which cover the observations from 2009 December 14 to 2010 September 29 (Wright 2010b; Wright et al. 2010; Mainzer et al. 2011). The NEOWISE data cover additional IR multiepoch data for W1 and W2 bands, and we utilized the NEOWISE 2021 data release, which contains multiepoch photometries between 2013 December 13 and 2020 December 13 (Mainzer et al. 2011, 2014). WISE has a 90-minute orbit and conducts \( \sim 14.1 \) average observations for the parent sample and \( \sim 14.7 \) average observations for the luminosity-declining AGN candidates over a \( \approx 1 \)-day period, and a given location is observed every 6 months, which means that one source has on average \( 16 \times 14-15 \) data points for a light curve spanning \( \sim 10 \) yr long.

In this study, we applied the cross-matching radius of \( 2'' \) with the SDSS coordinates of our sample. Out of the two bands, we used only the W1 band because (1) the W1 band traces a warmer dusty region of \( T \approx 900 \) K than that traced by the W2 band, that is, a smaller physical scale, and a corresponding response of the AD variability is shorter; and (2) the W1 band is more sensitive than the W2 band, which enables us to extract more sources even in a single exposure.

We obtained the \texttt{wlmpro} photometry and selected the photometries with the good flux quality with \( \text{ph} \textunderscore \text{qual} = \text{A or B} \), which selected the sources with \( S/N > 3 \), and also the photometries with no flux contamination by using \( \text{ccflag} = 0 \).

Based on the selection criteria above, we obtained the WISE W1 IR light curves for 7614 (parent sample) and all 57 sources (luminosity-declining AGN candidates) out of the 7653 and 57 sources, respectively.

We binned the cadence data shorter than 1 day and derived the median magnitude, and we call each longer-cadence observation a single epoch of observations. This means that there are typically 16 epochs of photometry with separations from 6 months to a maximum of nearly \( \sim 10 \) yr. The average number of detections per epoch is \( \sim 14 \) for the parent sample. Sometimes there are fewer detections in each epoch, and we used the epoch that has at least two detections with good photometric quality flags. We then followed the same method as Stern et al. (2018), who obtained the maximum and minimum magnitudes (\( W_{1 \text{max,min}} \), where \( \text{max,min} \) stands for the maximum and minimum magnitudes) from the multiple-epoch observation of each source and calculated the variability strength \( \Delta W_1 = |W_{1 \text{max}} - W_{1 \text{min}}| \).

Figure 6 shows a histogram of the sources as a function of \( \Delta W_1 \). The median variation of the parent sample is \( \langle \Delta W_1 \rangle = 0.35 \pm 0.18 \), which is significantly higher than that of Stern et al. (2018) with \( \langle \Delta W_1 \rangle \sim 0.2 \), because of the difference of the sample and the resulting inclination angle effect of the dusty tori. While our sample is purely type 1 AGNs with the face-on view of the central engine, the sample of Stern et al. (2018) also contains type 2 AGNs based on their nature of the WISE IR selection, and those type 2 AGNs would show less variation in \( \Delta W_1 \) since the emitting region of the W1 band is close to the sublimation region of the dusty region (e.g., Koshida et al. 2014), and dust obscuration reduces the observed
variability. We also checked this tendency by including the type 2 AGN sample of Mullaney et al. (2013; Mul13) containing also type 2 AGNs in gray. The left y-axis shows the number of sources for the parent sample and the catalog of Mullaney et al. (2013; Mul13), and the right axis shows the number for the luminosity-declining AGN candidates.

Figure 6 also shows a different distribution of \( \Delta W_1 \) between the parent sample and luminosity-declining AGN candidates, which shows a relatively larger \( \Delta W_1 \), whose \( p \)-value for these two populations is 0.02, implying a statistically significant difference in the samples. The median value for the luminosity-declining AGN candidates is \( \Delta W_1 = 0.41 \pm 0.18 \), which is larger than that of the parent sample (\( \Delta W_1 = 0.35 \pm 0.18 \)). This is suggestive that our luminosity-declining AGN candidates are on average more IR variable than the parent sample not only in the timescale of \( \sim 10^3 \) yr but also even in the timescale of \( \sim 10 \) yr, which is a corresponding timescale of changing-look (CL) AGNs (e.g., Stern et al. 2018).

The W1-band light curves of the 57 luminosity-declining AGN candidates show a variety of their IR variabilities; continuous increasing, decreasing, and a stochastic trend. Four sources show a significant flux increase in the W1 band, which might suggest a recovery from the slightly lower accretion. On the other hand, two sources show a clear continuous flux decline over \( \sim 10 \) yr. These two light curves are shown in Figure 7 with \( > \Delta W_1 \sim 0.49 \) mag (left; SDSS J211646) and with \( > \Delta W_1 \sim 0.34 \) mag (right; SDSS J111800), which suggests a continuous fading of the AGN dust emission over the past 10 yr. The change of the Eddington ratio for those two sources is from \( \lambda_{\text{Edd}} = 0.03 \) to \( \lambda_{\text{Edd}} = 0.02 \) for SDSS J211646 and from \( \lambda_{\text{Edd}} = 0.16 \) to \( \lambda_{\text{Edd}} = 0.12 \) for SDSS J111800. The remaining 51 sources show stochastic variabilities that are not classified as either of the continuous declining or increasing.

3.4. Multiepoch SDSS Optical Spectra Spanning 1–10 yr Time Gap

The \( \sim 10 \) yr long IR variability by the WISE W1 band indicates that the luminosity-declining AGN candidates tend to show large variabilities in both \( \sim 10 \) yr and \( \sim 10^3 \) yr. This motivates us to search the multiepoch spectra given that our sample is obtained from the SDSS spectral surveys. We searched for multiepoch spectra for our luminosity-declining AGN candidates. Out of the 57 luminosity-declining AGN candidates, 13 sources have the second-epoch spectra observed in the later SDSS eBOSS survey (Abazajian et al. 2009; Yanny et al. 2009; Dawson et al. 2013, 2016). The time difference between the first- and second-epoch spectra spans from \( \sim 1 \) to 14 yr.

Considering that the fiber sizes are different between the SDSS BOSS (2") and SDSS eBOSS (3"), the host galaxy continuum and the emission might contaminate strongly for the later SDSS eBOSS spectrum. On the other hand, this does not effect our study significantly, since our main motivation is to compare the central AD components and the broad emission lines, both of which are considerably smaller than the current SDSS aperture sizes, and their emission contributes equally to both of the spectra.

Based on the subtraction of the two-epoch spectra, we found four sources with a significant difference of the continuum and/or broad emission lines. The top panels of Figure 8 shows two AGNs with a clear continuum and the broad component difference between the two epochs, so-called CL AGNs (LaMassa et al. 2015; MacLeod et al. 2016; Stern et al. 2018). SDSS J1354 shows a disappearance of the blue excess continuum associating the AD emission and H/\( \beta \) broad component, as well as a weakened H/\( \alpha \) broad line, resulting a spectral type change from type 1 to type 1.9 (Osterbrock & Kosi 1976; Osterbrock 1977, 1981). SDSS J1305 shows a disappearance of the blue excess continuum and a weakened H/\( \beta \), resulting in a spectral type change from type 1 to type 1.8. We also summarized the spectral properties in Table 2.

The bottom panels of Figure 8 show two AGNs with a significant continuum flux change (appearance for SDSS J1308 and disappearance for SDSS J1413) stronger than 3\( \sigma \) error of the associating continuum, but they do not show a difference in broad emission components. We hereafter refer to those two
serves as CL behavior (CLB) AGNs to distinguish from the CL AGNs with a clear sign of the flux changes of the broad emission.

The detection rate of CL AGNs for our luminosity-declining AGN candidates is extremely high, reaching 15% (2/13), and even higher, 30% (4/13), if CLB AGNs are included. This is a much more efficient preselection method by one to two orders of magnitude than the previous CL AGN searches, which have a range of detection rates from 0.4% to 1.3% after the preselections. For example, Potts & Villforth (2021) selected the candidates by applying $\Delta g_{AB} > 0.16$ and found 6 sources out of the preselected 941 sources, whose success rate is $\sim 0.6\%$. Yang et al. (2018) also utilized the SDSS multiepoch spectra where one epoch is shown as a source category of "GALAXY," but the other epoch shows a different category of "QSO" (or vice versa). This method preselected 2023 candidates, and 9 sources were genuinely CL sources, whose success rate is $\sim 0.4\%$. The highest success rate was obtained through the study by MacLeod et al. (2016), who selected the candidates by applying the multiepoch optical magnitude difference of $|\Delta g_{AB}| > 1$ mag with a good S/N of $\sigma_g < 0.15$ mag. This method selected 1011 candidates, and 10 sources were CL AGNs, so the resulting success rate is 1.0%. This indicates that the long-term variability selection used in our study turns out to be an efficient method to search CL AGNs tracing the variabilities in $\sim 10$ yr timescale.

Figure 9 shows the ALLWISE and NEOWISE light curves of the four newly discovered CL and CLB AGNs. The black and gray solid vertical lines in each panel represent the observed MJD of the SDSS spectra at the emitting region of the WISE W1-band emission by considering the time delays between the AD and WISE W1 band. To estimate the light-travel time from the center to the emitting region of the W1 band, we utilize the relation of Barvainis (1987) with the additional $k$-correction as follows:

$$D_{sub}/pc = 1.3 \left( \frac{L_{bol,AD}}{10^{46} \text{ erg s}^{-1}} \right)^{0.5} \left( \frac{T(1+z)}{1500 \text{ K}} \right)^{-2.8},$$  \hspace{1cm} (5)$$

where we assume that the emitted blackbody emission produced by the dust temperature of $T = 850$ K was detected in the WISE W1 band.

Those observing epochs of SDSS spectra as shown in Figure 9 give a sign that, for SDSS J1413, the second epoch of the SDSS spectra was taken at the faintest phase of the light curve in NEOWISE, which is consistent with the "disappearing" sign in the SDSS spectra. In addition, the current NEOWISE light curve already reaches the same flux level as the ALLWISE fluxes, which are close to the first epoch of the SDSS spectra, suggesting that the current optical spectra might show an appearing feature again. For SDSS J1308, which shows an appearing feature, even though the two spectra are taken well before the ALLWISE light-curve range, the burst or bright-end phase might last until the current epoch.

Sheng et al. (2017) showed that CL AGNs show higher variabilities in the NEOWISE W1 band with $\Delta W1 > 0.4$ mag, which is consistent with the cases of SDSS J1354 and the CLB AGN SDSS J1413 with $\Delta W1 = 0.65$ and 0.61 mag, respectively. On the other hand, the NEOWISE and SDSS two-epoch spectra do not simultaneously cover the transient phase of CL AGNs for the remaining CL AGNs and CLB AGNs, and actually they show smaller W1 variabilities of $\Delta W1 = 0.14$ for J1305 and $\Delta W1 = 0.25$ for J1308. This result indicates that the combination of the SDSS two-epoch spectra and WISE variability further increases the probability to find such CL AGNs by expanding the variability time span by a factor of $\sim 2$ ($\sim 7000$ days).

3.5. Location of Luminosity-declining AGN Candidates in the BPT Diagram

Figure 10 shows the location of our luminosity-declining AGN candidates (blue circles) and the parent type 1 AGN sources (gray circles) in the BPT diagram plane. Here we limit our AGNs to the additional S/N cut for the emission lines, with S/N $\geq 5$ for the narrow H$_\alpha$, H$\beta$, and [N ii] $\lambda 6584$ components, which are necessary for the sources to plot in the BPT diagram. This reduces the sample to 44 luminosity-declining AGN candidates and 3042 parent sources.

Figure 10 demonstrates two important features of luminosity-declining AGN candidates. One is that luminosity-declining AGN candidates preferentially have higher $\log([\text{OIII}]/\text{H}\beta)$...
The median ratio of log(\[\text{OIII}] / \text{H} \beta) \geq 1.0, which likely originates from our selection criteria, requiring high observed \[\text{OIII}] \lambda5007 luminosity with log \(L_{\text{bol, [OIII] obs}} > 10^{45}\) erg s\(^{-1}\) as shown in Figure 3. The second is that luminosity-declining AGN candidates are located in a wider range of log(\[\text{NII}] \lambda6584/\text{H} \alpha), spanning −1.5 < log(\[\text{NII}] \lambda6584/\text{H} \alpha) < 0, but are located preferentially in the low ratio of log(\[\text{NII}] \lambda6584/\text{H} \alpha) < −0.5. The median ratio of log(\[\text{NII}] \lambda6584/\text{H} \alpha) is −0.52 ± 0.27 for the luminosity-declining AGN candidates and −0.24 ± 0.27 for the parent sample. The cumulative histogram in the bottom panel of Figure 10 shows a notable difference between the two populations, with a p-value of \(\sim 2 \times 10^{-8}\), showing a significant distribution difference. Groves et al. (2006) showed that the line flux ratio of log(\[\text{NII}] \lambda6584/\text{H} \alpha) depends strongly on the NLR gas metallicity, and Kawasaki et al. (2017) also demonstrated that such low log(\[\text{NII}] \lambda6584/\text{H} \alpha) ratio with log(\[\text{NII}] \lambda6584/\text{H} \alpha) = −1 to 0.5 cannot be described by the high ionization parameter alone, which is estimated from the oxygen line ratio diagrams of \[\text{OIII}] \lambda5007 / \[\text{OIII}] \lambda3727 and \[\text{OII}] \lambda6300 / \[\text{OIII}] \lambda5007. They defined a low-metallicity AGN if the sources have a flux ratio of log(\[\text{NII}] \lambda6584/\text{H} \alpha) = −1 to 0.5, because the nitrogen relative abundance is in proportion to the metallicity, and roughly half of the luminosity-declining AGN candidates fulfill such a criterion. This suggests that some of our luminosity-declining AGN candidates might be in an early chemical metal enrichment phase of galaxies (Kawasaki et al. 2017). Kawasaki et al. (2017) defined “BPT-valley” AGNs, which are selected based on the region above the sequence of Kauffmann et al. (2003) (black solid curve) and the low nitrogen abundance of log(\[\text{NII}] \lambda6584/\text{H} \alpha) < −0.5. They found that a significant fraction of these selected AGNs show low-metallicity features. We followed the same manner as Kawasaki et al. (2017) to select these BPT-valley sources from our parent type 1 AGN sample, which leaves 721 objects. To investigate whether BPT-valley sources have a similar variability feature to that shown in our luminosity-declining AGN candidates, we also calculate the log(\(\Delta W1\)) and \(\Delta W1\) for the BPT-valley population in our sample. The BPT-valley population shows log(\(\Delta W1\)) = −0.32 ± 0.40, which is slightly lower than the value of the parent sample of log(\(\Delta W1\)) = −0.02 ± 0.37, and it is statistically significant with a p-value of \(\sim 10^{-16}\). Our luminosity-declining AGN candidates show lower log(\(\Delta W1\)) of −1.07 ± 0.09, and therefore also the p-value of the distribution difference between the luminosity-declining AGN candidates and the BPT-valley population is \(\sim 10^{-16}\). Thus, the BPT-valley population and luminosity-declining AGNs are essentially.

Figure 8. Top panels: the rest-frame optical spectra of the luminosity-declining AGN candidates showing a CLB between the two epochs of the SDSS observations (the blue and red lines represent the first- and second-epoch ones, respectively). The observation dates are shown with units of MJD in the legend of each panel. Bottom panels: the subtracted spectrum between the two epochs (black) overlaid with the fitting curve of the theoretical AD of \(f_\lambda \propto \lambda^{-1}\) (orange) (Shakura & Sunyaev 1973).
different populations in terms of the obtained R values. That is, a low-metallicity environment alone cannot reproduce such a significant AGN luminosity decline.

The WISE variability is $\Delta W = 0.39$ for the BPT-valley population, which is between the luminosity-declining AGN candidates ($\Delta W = 0.41$) and the parent sample ($\Delta W = 0.36$). The BPT valley and the parent sample show a different distribution for the variability, which is also suggested by the p-value of 0.02, but show a similar one to our luminosity-declining AGN candidates, with a p-value of 0.6.

It is naively expected that the stellar mass of low-metallicity AGNs would reside in relatively low stellar mass galaxies, i.e., $M_* < 10^{10} M_\odot$, as shown in star-forming galaxies at each cosmic epoch (e.g., Tremonti et al. 2004; Erb et al. 2006; Lee et al. 2006). In addition, some studies suggest that AGNs in low stellar mass galaxies tend to show a higher AGN variability amplitude in the optical bands (e.g., Kimura et al. 2020; Burke et al. 2022), while some report that mass dependence is weak (Kormendy & Ho 2013). On the other hand, it is still not clear whether low-metallicity AGNs reside in low stellar mass galaxies. Considering that our sample is type 1 AGNs, the stellar mass is hard to constrain with the current sample set. Instead, we compare the BH mass distributions of each subgroup as an indicator of the stellar mass, which is inferred from the scaling relation between $M_{BH}$ and $M_*$ (e.g., Kormendy & Ho 2013). The median $M_{BH}$ of each subgroup is $\langle \log(M_{BH}/M_\odot) \rangle = 8.0, 7.8, and 7.8$ for luminosity-declining AGN candidates, BPT-valley AGNs, and the parent sample, respectively. Assuming the relation between $M_{BH}$ and $M_*$ of Kormendy & Ho (2013), the expected stellar mass is $\langle \log(M_*/M_\odot) \rangle = 10.3, 10.2, and 10.2$, respectively. This suggests that most of the luminosity-declining AGN candidates do not reside in low stellar mass galaxies with $M_* < 10^{10} M_\odot$, but reside in relatively massive ones. The BPT-valley AGNs also show a similar trend, and this relatively massive stellar mass of the host galaxies, $M_* > 10^{10} M_\odot$, is consistent with the result of Kawasaki et al. (2017). One possible mechanism of such low-metallicity AGNs in the relatively massive host galaxies can be realized if the inflow of the low-metallicity gas occurs from the intergalactic medium and/or surrounding environment (Husemann et al. 2011).

### 4. Discussion

#### 4.1. How Long Does Super-Eddington Phase Last?

Our study shows that there are variable AGNs in the time span of $10^3$–$10^4$ yr, and their AGN luminosities used to reach near the Eddington limit. This suggests that the lifetime of such a burst phase around the Eddington limit ($t_{burst}$) may not last long, a timescale of $10^3$–$10^4$ yr. Since the Eddington ratio is estimated for all samples in this study at the three epochs as shown in Figure 5, we here estimate $t_{burst}$ from the number fraction of such a super-Eddington phase at each epoch.

We first count the number of sources above the Eddington limit at each AGN indicator, $N_{i,Edd}$ (where $i = \text{NLR}$, torus, or AD), and if the sources are above the Eddington limit in the two epochs, those numbers are written as $N_{i,+Edd}$, where $i = \text{NLR}$, torus, and AD and $D_i > D_j$. Since the $\lambda_{Edd}$ has a certain error, we treat the source as a super-Eddington source only when the $\lambda_{Edd} - 3\Delta\lambda_{Edd} > 1$. Then, we calculate the number fraction that are beyond the Eddington in both the torus and NLR indicators, and the obtained fraction is $f_{Edd} = N_{NLR+torus,Edd}/N_{NLR,Edd} = 15/114 = 0.13$. We assume that the burst phase lasts with a stable luminosity for the time span of $t_{burst}$. In this case, $t_{burst} = 0.36$, as shown in Figure 5, we here estimate $t_{burst}$ from the number fraction that are beyond the Eddington in both the torus and NLR, and essentially it is dominated by the look-back time $t_{burst}$.

$$ t_{burst} = \exp\left(-\frac{\Delta t}{t_{burst}}\right), \quad (6) $$

where $\Delta t$ is the look-back time difference between the torus and NLR, and essentially it is dominated by the look-back time to the NLR, with $\Delta t \sim 10^3$–$10^4$ yr (see Figure 5). Thus, $t_{burst} = -\Delta t/\log(f_{Edd}) \approx 6 \times 10^3$ yr.\(^8\) This is four to five orders of magnitude shorter than the total lifetime of AGNs of $\sim 10^8$ yr (Marconi et al. 2004), and even one to two orders of magnitude shorter than the typical one-cycle ($t_{AGN}$) AGN lifetime of $10^7$ yr (Schawinski et al. 2015). Therefore, super-Eddington phase can be achieved a certain fraction of the AGN lifetime of $t_{burst,Edd} = f_{burst}/t_{AGN} \sim 0.01$–$0.1$.

Although $t_{burst,Edd}$ is small and our sample is based on low-$z$ high-luminosity type 1 AGNs in the low-$z$ universe at $z < 0.4$, the suggested $t_{burst,Edd} \sim 0.1$ might alleviate the current challenge to the quasar evolution as seen in $z > 6$, where most of the luminous quasars require the Eddington limit accretion with the duty cycle of nearly one (Willott et al. 2010; Mortlock et al. 2011; Wu et al. 2015; Bañados et al. 2018; Wang et al. 2021; Yang et al. 2021). Assuming that the luminous quasars experience a super-Eddington phase with 10% of their quasar lifetime, the accretion rate can exceed the Eddington limit by a factor of up to $\sim 10$–$100$ (Obşuga et al. 2005; Jiang et al. 2014; Sadowski et al. 2015; Inayoshi et al. 2016, 2020), which reduces the required quasar growth time by a factor of 2–10.

Recently, the lifetimes of high-$z$ ($z > 6$) quasars have been reported through the measurements of the physical extents of hydrogen Ly$\alpha$ proximity zones (Eilers et al. 2018; Davies et al. 2020; Eilers et al. 2021). Some sources show a small physical size, and therefore the inferred quasar lifetime is substantially short, on the order of $10^3$–$10^4$ yr. Given that the inferred quasar lifetimes of such $z > 6$ quasars are substantially shorter than the $e$-folding timescale of the Eddington-limited accretion with $t_{Edd} \approx 4.5 \times 10^5$ yr, Inayoshi et al. (2021) suggested that those quasars are expected to experience the super-Eddington accretion phase to grow up. This short timescale of $10^3$–$10^4$ yr is consistent with our expected $t_{burst}$ of the super-Eddington phase of local AGNs at $z < 0.4$. This might be a coincidence.

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\(^8\) Using a 2$\sigma$ instead of 3$\sigma$ selection criterion for super-Eddington phases would give us $t_{burst} \approx 10^3$ yr, which has little impact on the estimation of $t_{burst}$. 

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| Name          | SDSS OBJID DR7 | R.A. (deg) | Decl. (deg) | $z$ | Changing-look Feature | Type |
|---------------|----------------|------------|-------------|-----|------------------------|------|
| SDSS J135415.53+515925.7 | 587733410444607498 | 208.56 | 51.99 | 0.32 | turning off | CL |
| SDSS J130501.41+604204.9 | 587732592255434858 | 196.26 | 60.70 | 0.38 | turning off | CL |
| SDSS J130842.24+021924.4 | 587726015076433954 | 197.18 | 2.32 | 0.14 | turning on | CLB |
| SDSS J141324.21+493424.9 | 588017713123557439 | 213.35 | 49.57 | 0.37 | turning off | CLB |
but it is seen in both quasars at $z > 6$ and $z < 0.4$. If a constant $t_{\text{burst}} \sim 0.1$ of the super-Eddington phase is ubiquitously seen across the cosmic epoch, the lifetime of such a super-Eddington phase would be fundamentally governed by the BH AD physics and unrelated to the cosmological environment once enough gas supply is achieved into the central engine.

### 4.2. What Are Luminosity-declining AGN Candidates in This Study?

Our goal is to search for luminosity-declining AGNs that have experienced a large flux decline in the past $10^3$–$10^4$ yr, and we selected 57 $[\text{O III}] \lambda 5007$ bright and MIR faint AGNs as luminosity-declining AGN candidates. Figure 5 exhibits that our method selects sources that experienced burst phase reaching the Eddington limit and rapidly declined AGN luminosities at least by a factor of 10 in the last $10^3$–$10^4$ yr.

In addition to such a feature in the long-term flux change of the $\sim 10^3$–$10^5$ yr span, a certain fraction of such luminosity-declining AGN candidates also show variabilities even in the last $\sim 10$ yr scale, which has been supported from the NEOWISE light curve and the SDSS multiepoch spectra with high cadence of the CL AGN feature. This suggests that our method turns out to be an efficient way to select not only for a long-term AGN variability of $\sim 10^3$–$10^4$ yr but also for a relatively shorter-term AGN variability with $< 10$ yr timescale.

Several authors have already discussed that the flux change of $\sim 10$ yr timescale, notably for CL AGNs, has a different physical origin from the one shown in fading AGNs with a
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~10^3–10^4 yr timescale. The latter timescale is roughly consistent with the viscous timescale, an inflow timescale of the gas accretion, and can be realized once rapid accretion rate change occurs in the AD (see, e.g., discussions in Ichikawa et al. 2019a, 2019c). It was discussed that the origin of the flux change in the time span of ~1 to ~10 yr rather originates from the instability of the AD (LaMassa et al. 2015; Ruan et al. 2016; MacLeod et al. 2016; Stern et al. 2018).

One key insight obtained from this study is that the two-epoch spectra are obtained with the time span of 1–14 yr, and the average BH mass of the sample is (M_{BH}) ∼ 10^8 M_⊙. This suggests that the observed CLB should occur within ~10 yr in the system of (M_{BH}) ∼ 10^8 M_⊙. This can rule out some disk timescales as origins of the CLB. For example, the heating and cooling front propagation instability in the disk occurs in the timescale of t_{front} ∼ 20(M_{BH}/10^8 M_⊙) yr by assuming that the scale height of the disk is h/R = 0.05 and the disk viscous parameter is α = 0.03. Since our observing epoch covers the time span of 14 yr at the maximum, the characteristic cooling front timescale might match with the CL events shown in our sources. On the other hand, the thermal timescale of the disk, which can be written as t_{th} ∼ 1 × (M_{BH}/10^8 M_⊙) yr, is slightly too short.

Noda & Done (2018) noted that such CL AGN behavior is tightly connected to the state change, and such a change preferentially occurs at a specific Eddington ratio range of around log λ ∼ −1 to −1.5 and a timescale of several years. Considering that most of our luminosity-declining AGN candidates have Eddington ratio of around this range and their timescales are also consistent with the expectation from Noda & Done (2018), this might be related to such a state change and our sample might preferentially pick up CL AGNs with the association of the state change.

In summary, the origins of the possible connection of the luminosity change between the 10 yr timescale and 10^3–10^4 yr are still uncertain, but the preference of the CLB at the specific Eddington ratio of log λ_{Edd} ∼ −1 to −1.5 and the ~10^3 yr long burst phase at the Eddington ratio of log λ_{Edd} ∼ 0 suggests that both timescales might connect to the state transition events in the AD. Although the current sample still limits the sample size to only four sources that experienced the variations in both 10 and 10^3 yr, the incremental sample will happen soon once the eROSITA (Predehl et al. 2021) X-ray all-sky data become public at the beginning of 2023. eROSITA will provide the current AGN luminosity for our type 1 AGN sample without worrying about the dust or gas obscuration to the line of sight. In addition, the 0.5–2 keV flux limit of eROSITA in the final integration of the planned 4 yr program (eRASS8) in the ecliptic equatorial region (f_{0.5–2keV} = 1.1 × 10^{−14} erg s^{-1} cm^{-2}) Predehl et al. 2021) is way deeper than the expected one estimated from the WISE W3 (12 μm) band flux density limit, where f_{1.6μm} = 1 mJy corresponds to f_{0.5–2keV} = 8.3 × 10^{−14} erg s^{-1} cm^{-2}, by assuming the local X-ray–MIR luminosity correlation of AGNs (Gandhi et al. 2009; Ichikawa et al. 2012; Asmus et al. 2015; Ichikawa et al. 2017).

4.3. Radio Properties of Luminosity-declining AGNs

We here discuss the radio properties of the luminosity-declining AGNs since most of the [O III] λ5007 luminous extremely red quasars at z ∼ 2–3 (Ross et al. 2015; Hamann et al. 2017) are known to be radio-bright sources with ν/L_{1.4GHz} ∼ 10^{40}–10^{41} erg s^{-1} (e.g., Zakamska & Greene 2014; Hwang et al. 2018), which likely originate from shocks caused by wide-angle quasar winds, and it is worth checking whether our sources could be local (z < 0.4) analogous to them.

Mullaney et al. (2013) summarized the radio properties of our parent sample based on the 1.4 GHz radio detections by the Very Large Array/FIRST (Becker et al. 1995; White et al. 1997; Helfand et al. 2015) and NVSS (Condon et al. 1998) surveys at a limiting flux density of >2 mJy, by following a similar manner to Best et al. (2005). Out of our 57 luminosity-declining AGN candidates, 7 sources have such radio detections with the median radio luminosity of L_{1.4GHz} ∼ 10^{24} W Hz^{-1} or νL_{1.4GHz} ∼ 10^{40} erg s^{-1}, whose radio-to-bolometric luminosity ratio is log(νL_{1.4GHz}/L_{bol,(10^{10} L_{⊙})}) ∼ −6.2, which is comparable to the value expected from the quasar wind scenario (e.g., Hwang et al. 2018).

The radio detection rate of luminosity-declining AGNs is 7/57 ≈ 0.12, which is slightly higher than that of our parent sample of 460/7653 ≈ 0.06 and is closer to the detection rate of the extremely red quasars of 9/97 ≈ 0.09 at the same radio survey depth. Although the sample size is too small at this stage, such a higher radio detection rate might be a result of the enhancement of the radio emission by the shocks from the AGN radio-driven outflow, as discussed in Zakamska & Greene (2014). If our luminosity-declining AGNs are in a similar population of extremely red quasars at z = 2–3, luminosity-declining AGNs are also likely in the middle of the strong AGN feedback phase with a strong radiative outflow, and this scenario is also consistent with the experience of the AGN luminosity declining over the past 10^3–10^4 yr partially because of the short supply of gas into the nucleus. However, we also note that the additional deeper radio observations are necessary to confirm that similar radio properties can be obtained for the remaining FIRST or NVSS nondetected luminosity-declining AGNs.

Some might also wonder whether blazars might contaminate the sample of luminosity-declining AGNs. For the seven radio-detected sources in our sample, their optical spectra are dominated by the strong emission lines, as well as the blue continuum, which is a natural outcome based on our selection criteria of type 1 AGNs with strong [O III] λ5007 emission lines with S/N ≥ 5. This rules out a possibility that they are BL Lac sources whose optical continuum should not show any emission lines. In addition, their 1.4 GHz radio luminosity is around νL_{1.4GHz} ∼ 10^{40} erg s^{-1}. This is at least one order of magnitude fainter than the typical observed radio luminosity range of the flat-spectrum radio quasars (e.g., Ghisellini et al. 2017). Based on those results, we conclude that blazar contamination is unlikely for our seven radio-detected luminosity-declining AGNs (see also the discussions in Ichikawa et al. 2021).

5. Conclusion

We systematically search for an AGN population that has experienced a significant AGN luminosity decline in the past 10^3–10^4 yr by utilizing the advantage of the difference of the physical size of each AGN indicator, spanning from <1 pc to ≥1 kpc. We cross-matched the ~7700 SDSS DR7 type 1 AGNs at z < 0.4 (Mullaney et al. 2011), covering the [O III] λ5007 emission line, which is a tracer for the roughly kiloparsec-scale NLR emission, with the WISE IR catalog, which traces the AGN dust emission in the central ~10 pc scale. With our selection of at least one magnitude fainter in the AGN dust luminosity than the one from the NLR, we selected an interesting population of the luminosity-declining AGN
candidates that have experienced an AGN luminosity decrease by a factor of $>10$ in the previous $10^3$–$10^4$ yr. The sample contains 57 AGNs, and our results show interesting properties that give key insights to the BH and AD physics as written below.

1. The parent type 1 AGN sample shows on average the constant Eddington ratio over the previous $10^3$–$10^5$ yr, indicating that the intrinsic AGN variability within $\sim 10^3$–$10^5$ yr should be on average smaller than the scatter of 0.4 dex. On the other hand, the luminosity-declining AGN candidates show a large luminosity decline in the previous $10^3$–$10^4$ yr, and their previous AGN luminosities reached near the Eddington limit of $\log \lambda_{\text{Edd}} \sim 0$, while the current Eddington ratio is similar to those of the parent sample of $\log \lambda_{\text{Edd}} \sim -1.5$, indicating the drastic luminosity decline by a factor of $>10$.

2. Utilizing the 3.4 $\mu$m light curves obtained from ALLWISE and NEOWISE, the luminosity-declining AGN candidates show a relatively larger W1-band variability of 0.41 compared to the parent sample of 0.35. In addition, two sources show a continuous flux decline over $\sim 10$ yr, suggesting that at least two sources still experience the luminosity decline in the past $10$ yr, a possible continuous flux decrease over $10^3$ yr.

3. Thirteen out of the 57 luminosity-declining AGN candidates have multiepoch SDSS spectra, and two of them show a spectral type change associated with a disappearing continuum and broad-line emissions, which might also be an efficient method to select AGNs that have recently experienced the AGN variability in the past $\sim 10$ yr.

4. The location of the luminosity-declining AGN candidates in the BPT diagram is different from the parent type 1 AGN sample, notably a lower median flux ratio of log ([N II] $\lambda 6584$/H$\alpha$ $\lambda 6563$) $= -0.52$ compared to log ([N II] $\lambda 6584$/H$\alpha$ $\lambda 6563$) $= -0.24$ for the parent sample. Considering that the lower flux ratio indicates that their NLR gas has a lower gas metallicity, luminosity-declining AGN candidates might prefer the host galaxies with younger and gas-rich host galaxies, resulting in the past AGN burst reaching the Eddington limit accretion.

5. Utilizing this long-term light curve, we estimate the lifetime of the burst phase realizing the super-Eddington accretion. The estimated lifetime is $t_{\text{burst}} \sim 10^5$ yr, suggesting that the super-Eddington phase can be achieved only in a certain fraction of the AGN lifetime of $t_{\text{burst}}/\lambda_{\text{AGN}} \sim 0.01$–0.1.

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Software: Astropy (Astropy Collaboration et al. 2018), Matplotlib (Hunter 2007), Pandas (McKinney 2010).

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