Search for Intermediate-mass Black Holes at Low Redshift with Intra-night Variability

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Abstract

We present a sample of intermediate-mass black hole (IMBH) candidates based on the detection of a broad Hα emission line and variability, which are selected from the Sloan Digital Sky Survey Data Release 7. By performing spectral decomposition of emission lines as well as a visual inspection, we initially identified 131 targets with a broad Hα line among a large sample of emission line galaxies. We further selected 25 IMBH candidates whose estimated black hole mass (\(M_{\text{BH}}\)) is less than \(10^6 M_\odot\). To constrain the nature of these candidates, we analyzed X-ray properties and performed an intra-night variability monitoring campaign with optical telescopes. Based on the optical variability analysis, we report a sample of 11 targets with detected intra-night variability as the best IMBH candidates, which are suitable for follow-up observations for accurate \(M_{\text{BH}}\) determination such as reverberation mapping campaigns.

Unified Astronomy Thesaurus concepts: Intermediate-mass black holes (816); Low-luminosity active galactic nuclei (2033)

1. Introduction

Decades-long observations have established that supermassive black holes (SMBHs) with masses \(>10^6 M_\odot\) are universal in the center of massive galaxies at low redshift (e.g., see Kormendy & Richstone 1995; Kormendy & Ho 2013), yet the origin and the mass range of the high-redshift seeds of these SMBHs are unclear. The existence of stellar mass black holes (BHs) in a much lower mass range \(\sim 10^{-3}-100 M_\odot\) has been well studied by various observations of electromagnetic radiation as well as gravitational waves (e.g., Remillard & McClintock 2006; Thompson et al. 2019; Abbott et al. 2020). However, discovery of a \(\sim 10^3 M_\odot\) SMBH in the very early universe triggered a fundamental question about BH formation and the seed mass (Mortlock et al. 2011; Bañados et al. 2018; Onoue et al. 2019). One of the scenarios suggests that the progenitor of the high-\(z\) SMBHs is much heavier than a normal stellar mass BH (e.g., Loeb & Rasio 1994; Latif et al. 2013; Greene et al. 2020).

Thus, by bridging the two well-observed \(M_{\text{BH}}\) ranges, a systematic search of intermediate-mass black holes (IMBHs) with masses of \(10^{-3}-10^2 M_\odot\) in the present-day universe is pivotal to understand how the seeds of SMBHs formed and evolved throughout cosmic time (e.g., Volonteri et al. 2008; Greene 2012; Greene et al. 2020). If some of the seed BHs at high redshift remain as IMBHs without significantly growing over cosmic time, the relics of the seeds can be observed in nearby galaxies as IMBHs (e.g., Greene 2012; Reines & Comastri 2016; Mezcua 2017; Woo et al. 2019a).

Nevertheless, IMBHs are rarely observed, hence, they are called the “missing link” between stellar mass BHs and SMBHs (see the review by Mezcua 2017). The evidence of IMBH candidates has been found from various observations. First, X-ray emission and the dynamical modeling of a number of globular clusters (GCs) suggested the presence of an IMBH in their centers (e.g., Gebhardt et al. 2000; Gerssen et al. 2002; Pooley & Rappaport 2006). For example, Silk & Arons (1975) first argued that the X-ray flux from their GC targets could be explained by the accretion of IMBHs with masses in the range \(100-1000 M_\odot\). Baumgardt (2017) also claimed that an IMBH with a mass of \(\sim 4 \times 10^4 M_\odot\) exists in \(\omega\) Centauri by analyzing the velocity dispersion profile of the stars in the GC. Tens of IMBH candidates were identified in similar ways, but their methodologies depended on complicated models of kinematics and radiation, limited to nearby IMBH candidates. Second, extragalactic ultra-luminous X-ray sources (ULXs) were proposed to be IMBHs. BH mass estimation based on the fundamental plane of accreting BHs (e.g., Webb et al. 2012; Cseh et al. 2015) and X-ray spectrum fitting (e.g., Miller et al. 2003; Sutton et al. 2012) indicated that several BHs were in the IMBH mass range. These methods required multiwavelength observations, including the X-ray and radio, along with complex modeling of the accretion disk.

Detection of broad emission lines, which are one of the main signatures of mass-accreting type 1 active galactic nuclei (AGNs), also provided evidence for IMBH candidates (e.g., Filippenko & Ho 2003; Greene & Ho 2004, 2007; Dong et al. 2012). Compared with the other methods, this method enables discovery of IMBH candidates in distant galaxies, and the masses of these candidates can be better determined. Assuming that the gas in the broad line region (BLR) is virialized and governed by the gravitational potential of the central BH, the mass of the BHs can be determined based on the virial relation:

\[
M_{\text{BH}} = f \times R_{\text{BLR}} \Delta V^2 / G
\]

where \(R_{\text{BLR}}\) is the BLR size, \(\Delta V\) is the velocity of gas measured from the width of broad emission lines, and \(f\) is a dimensionless scale factor depending on the kinematics and geometry of the BLR (e.g., Peterson 1993; Peterson et al. 2004). Adopting the correlation between AGN continuum luminosity (or emission line luminosity) and the BLR size (e.g., Bentz et al. 2013), the BH mass can be indirectly estimated.
based on single-epoch spectra (e.g., Woo & Urry 2002; Greene & Ho 2005; Park et al. 2012; Shen & Liu 2012; Le et al. 2020).

Among the broad emission lines, the Hα line is often utilized to identify type 1 AGNs because of its high intensity (e.g., Woo et al. 2014; Eun et al. 2017). While typical type 1 AGNs with strong Hα have $M_{BH}$ larger than $10^6 M_\odot$, a relatively weak broad Hα line should be present in AGNs with an intermediate-mass BH. Thus, a number of studies utilized the presence of a weak broad Hα line to search for IMBHs (e.g., Greene & Ho 2004, 2007; Dong et al. 2012; Reines et al. 2013; Chilingarian et al. 2018; Liu et al. 2018).

For example, Reines et al. (2013) identified IMBH candidates, whose host galaxy stellar masses are smaller than $3 \times 10^9 M_\odot$, by detecting a weak broad component of the Hα line in a sample of galaxies at $z < 0.055$ by assuming that IMBHs are more likely to exist in dwarf galaxies as suggested by the BH mass–stellar mass relation (e.g., Greene 2012; McConnell & Ma 2013; Reines & Comastri 2016). Based on the broad Hα, they reported 17 IMBH candidates; however, additional studies are required to confirm their masses because the mass estimation based on the single-epoch spectrum analysis suffers from a large uncertainty, and it is possible that other sources such as luminous blue variable stars may be responsible for the broad Hα (e.g., Izotov & Thuan 2007, 2009b).

The true nature of IMBH candidates can be constrained by other properties of type 1 AGNs. For example, detection of high-luminosity X-ray emission can provide a constraint to confirm whether they are mass-accreting BHs, since AGNs are sources of strong X-ray radiation (e.g., Elvis et al. 1978; Nucita et al. 2017; Chilingarian et al. 2018; Liu et al. 2018). Variability also provides strong constraints, as the AGN continuum and emission line flux changes over time (e.g., Rodríguez-Pascual et al. 1997; Walsh et al. 2009; Reines & Stalin 2017; Baldassare et al. 2018; Martínez-Palomera et al. 2020). In the case of an IMBH, a variability test over an intra-night or several day timescale is a crucial tool for identification of these candidates (e.g., Mushotzky et al. 2011; Aranzana et al. 2018; Kim et al. 2018).

In this paper we present the results of our systematic search for IMBH candidates. By detecting the Hα emission line and focusing on the targets with the weakest Hα broad component, we identified a sample of IMBH candidates. Then, we investigated X-ray properties and intra-night variability. We describe the sample selection in Section 2, observations and the data reduction in Section 3, and the variability analysis in Section 4. We provide a discussion in Section 5, and summary and conclusion follow in Section 6.

2. Sample Selection

2.1. Local AGN and Star-forming Galaxy Sample

To find IMBH candidates by detecting a weak Hα broad component, we started with a large sample of emission line galaxies from Bae & Woo (2014) and Woo et al. (2016), who classified 60,018 type 2 AGN-host galaxies and 128,951 star-forming galaxies (SFGs) based on the flux ratios of the emission lines (Kauffmann et al. 2003), using the Max Planck Institute for Astrophysics and the Johns Hopkins University (MPA–JHU) catalog of Sloan Digital Sky Survey (SDSS) DR7 galaxies (Abazajian et al. 2009). For robust spectral analysis, they restricted the sample with two criteria: (1) a signal-to-noise ratio $(S/N) > 3$ for the four emission lines, Hβ, [O III] λ5007, Hα, and [N II] λ6584; (2) amplitude (peak) to noise ratio $(A/N) > 5$ for both the Hα and [O III] λ5007 emission lines. Based on these criteria, we selected 10,958 type 2 AGNs at $z < 0.1$. We also obtained 22,000 SFGs at $z < 0.1$ by limiting the stellar mass of the host galaxy to $M_\star < 10^9 M_\odot$ in order to survey dwarf galaxies, which are more likely to host IMBHs (e.g., McConnell & Ma 2013; Reines & Comastri 2016).

2.2. IMBH Candidates with a Broad Hα Component

2.2.1. Spectral Decomposition

We performed spectral decomposition to investigate the presence of a broad Hα component using the selected AGNs and SFGs. It is crucial to decompose AGN emission lines from the host galaxy stellar continuum to properly measure the flux and velocity dispersion of Hα. We first subtracted the stellar continuum from the SDSS spectra by using the penalized pixel-fitting (pPXF) routine (Cappellari & Emsellem 2004), which finds the best-fit stellar template for the given galaxy spectrum. For this process, we used MILES simple stellar population models with solar metallicity (Sánchez-Blázquez et al. 2006). Before the fitting process, we masked the optical emission lines and the Hα emission line region (i.e., 6300–6900 Å) to prevent fitting a potential broad emission line as a stellar continuum. We then subtracted the best-fit continuum model from the observed spectra, leaving the pure emission line spectra.

Then, we constructed the emission line model for the region around Hα (i.e., 6400–6800 Å), where the [N II] λ6548, [N II] λ6584, [S II] λ6717, and [S II] λ6731 lines are also located. To confirm the presence of a broad Hα component, we used four different fitting schemes: (1) a fit to the narrow component of each emission line ([N II], [S II], and Hα) using a single Gaussian model, without including an additional Gaussian model for a potential broad Hα line, (2) a fit to the narrow component with a double Gaussian model without including an additional broad Hα component, (3) a fit to the narrow component with a single Gaussian model with the addition of one more Gaussian model for a broad Hα line, and (4) a fit to the narrow component with a double Gaussian model, including an additional model for a broad Hα line. We fixed the relative separations between the centers of each emission line model to the laboratory value, and the width of each narrow emission line to the equivalent value assuming that they are emitted from the cloud with the same kinematical properties. Furthermore, in the double Gaussian model for narrow components, we added a constraint that the amplitude ratio of the two Gaussian components should be equal for each emission line model.

For modeling, we used the `curve_fit` tool of the Python `scipy` package (Virtanen et al. 2020), which utilizes a trust region reflective algorithm. To evaluate the reliability of the fitting results, we calculated their reduced chi square ($\chi^2_{\text{red}}$) and Bayesian information criterion (BIC) as

$$\chi^2_{\text{red}} = \frac{1}{n - m} \sum_i \frac{(O_i - C_i)^2}{\sigma_i^2}$$

and

$$\text{BIC} = \sum_i \frac{(O_i - C_i)^2}{\sigma_i^2} + m \ln n$$

where $O_i$ is the observed flux density at each wavelength, $C_i$ is the model flux density, and $\sigma_i$ refers to the flux density error. They both consider the number of the data points ($n$) and the
number of the model parameters \((m)\). Similar to \(\chi^2_{\text{red}}\), a better fitting model has a smaller BIC. However, the BIC has a penalty term \((m \ln n)\) for the number of the model parameters, so a more reliable comparison can be done between the models with different numbers of parameters. When the difference between the BIC values of two models is greater than 10, it is rated as strong evidence against the significance of the model with the higher BIC (Kass & Raftery 1995).

Based on the results, we set the criteria to select the candidates with a broad H\(\alpha\) line. To prevent the overfitting problem, we employed a single Gaussian model for the narrow component if the BIC of model (1) is less than the BIC of model (2) + 10; if not, we used a double Gaussian model for the narrow component. We initially selected the candidates that have a broad H\(\alpha\) line using criteria as follows.

1. Velocity dispersion of an H\(\alpha\) broad component after correcting for the SDSS instrumental resolution (60 km s\(^{-1}\)) > 250 km s\(^{-1}\) (i.e., \(\sim\)590 km s\(^{-1}\) FWHM).
2. A/N of an H\(\alpha\) broad component \(>20\) (10 for SFGs).
3. BIC of the model with an H\(\alpha\) broad component + 10 < BIC of the model without an H\(\alpha\) broad component.
4. \(\chi^2_{\text{red}}\) of the model with an H\(\alpha\) broad component + 10 < \(\chi^2_{\text{red}}\) of the model without an H\(\alpha\) broad component.

The adopted lower limit of the velocity width (i.e., a velocity dispersion of 250 km s\(^{-1}\) or FWHM = \(\sim\)590 km s\(^{-1}\) FWHM) seems lower than the typical definition of type 1 AGNs (i.e., \(>1000\) km s\(^{-1}\) FWHM; e.g., Vanden Berk et al. 2006). However, a velocity dispersion of 250 km s\(^{-1}\) is much larger than the stellar velocity dispersion due to the gravitational potential of low-mass galaxies. Instead, the line broadening is likely caused by the gravitational potential of low-mass IMBH candidates with a broad H\(\alpha\) line. To prevent the overfitting problem, the broad component must be fixed by the same value, the model without a broad H\(\alpha\) component makes the [S II] line model much broader than the best-fit model.

There are also examples of the opposite case shown in the Appendix. If a model without a broad H\(\alpha\) model fits the [S II] lines, it makes the H\(\alpha\) line model much narrower than does the best-fit model, so a significant residual is present around the H\(\alpha\) line. By contrast, the model with a broad H\(\alpha\) component fits both the [S II] and H\(\alpha\) emission line better. Based on the visual inspection, we found 738 candidates from type 2 AGNs and four candidates from SFGs.

### 2.2.2. Black Hole Mass Estimation

We estimated BH masses \((M_{\text{BH}})\) for the sample of 738 type 1 AGNs with a broad H\(\alpha\) to select the IMBH candidates. Note that 611 targets among 738 objects were previously studied by Eun et al. (2017). Since their estimated BH masses are larger than \(10^6 M_\odot\), we excluded them from the sample of IMBH candidates. For the remaining 131 AGNs, we determined \(M_{\text{BH}}\) using a single-epoch estimator based on the virial assumption and the BLR size–luminosity \((L_{1000})\) relation (Bentz et al. 2013). Because the H\(\alpha\) luminosity can be used as a proxy for the AGN continuum luminosity (Greene & Ho 2005),

\[
L_{\text{H}\alpha} = \left( \frac{5.25 \pm 0.02}{(1.157 \pm 0.005)} \right) \times 10^{42} \left( \frac{L_{5100}}{10^{44} \text{ erg s}^{-1}} \right) \text{ erg s}^{-1},
\]

we determined \(M_{\text{BH}}\) using the velocity dispersion \((\sigma_{\text{H}\alpha})\) and luminosity \((L_{\text{H}\alpha})\) of the H\(\alpha\) broad component (Woo et al. 2015):

\[
M_{\text{BH}} = f \times 10^{(5.56 \pm 0.06) \pm (L_{\text{H}\alpha}) \pm (2.06 \pm 0.06)} \times \left( \frac{\sigma_{\text{H}\alpha}}{10^6 \text{ km s}^{-1}} \right)^{(0.46 \pm 0.03)} \times \left( \frac{L_{\text{H}\alpha}}{10^{42} \text{ erg s}^{-1}} \right) M_\odot,
\]

where \(\log f = 0.65 \pm 0.12\) is the virial factor.

We determined the error of each model parameter by calculating the square root of the diagonal term of the covariance matrix provided by the \texttt{curve_fit} tool, and calculated the measurement uncertainty of \(M_{\text{BH}}\) using standard propagation of the errors. Considering the intrinsic scatter of the size–luminosity relation (0.19 dex; Bentz et al. 2013) and the uncertainty of the virial factor (0.12 dex; Woo et al. 2015) as systematic uncertainties, we obtained the total error of \(M_{\text{BH}}\) by adding the measurement and systematic uncertainties in quadrature. The combined error is typically \(\sim\)0.24 dex.

In Figure 2, we present the distribution of the H\(\alpha\) luminosity, velocity dispersion, and \(M_{\text{BH}}\) of the 131 type 1 AGNs. The estimated \(M_{\text{BH}}\) is in the range \(\sim 10^{-3} \text{ to } 10^{-2} M_\odot\) with a median of \(10^{6.3} M_\odot\), while we found no target with \(M_{\text{BH}} < 10^6 M_\odot\). Among them, we identified 25 targets with \(M_{\text{BH}} < 10^6 M_\odot\) as IMBH candidates.

### 2.3. X-Ray Black Hole Candidates

To find additional evidence that the selected 131 targets with a broad H\(\alpha\) line are AGNs, we investigated X-ray properties by retrieving the X-ray flux data from the online archive NASA/IPAC Extragalactic Database\(^5\) and the NASA HEASARC Xamin Web interface.\(^6\) For 19 targets we obtained X-ray flux data between 0.1 and 150 keV using archival data of various X-ray missions (see Table 1). The measured X-ray luminosity ranges from \(\sim 10^{37}\) to \(10^{41} \text{ erg s}^{-1}\) with a median luminosity of \(\sim 10^{39.3} \text{ erg s}^{-1}\). However, the estimated \(M_{\text{BH}}\) values of these targets are larger than \(10^6 M_\odot\), resulting in no IMBH candidate.

\(^5\) https://ned.ipac.caltech.edu/

\(^6\) https://heasarc.gsfc.nasa.gov/xamin/
with available X-ray luminosity. Note that the targets with \( M_{\text{BH}} \) close to \( 10^6 M_\odot \) can be IMBHs if we consider relatively large uncertainty of the estimated \( M_{\text{BH}} \).

### 2.4. Pilot Sample for a Variability Test

Using the selected 25 IMBH candidates, we performed an optical variability test in order to confirm them as AGNs. In addition, we also observed the IMBH candidates from Reines et al. (2013) as complementary candidates, for which no optical variability test has been performed by Reines et al. (2013). By applying the same criteria (\( M_{\text{BH}} < 10^6 M_\odot \)) to the sample of Reines et al. (2013), we found 16 targets as IMBH candidates. Only one target overlaps with our sample of 25 objects. Note that there are differences between the work of Reines et al. (2013) and ours due to the details of the spectral decomposition. Unlike in this study, for example, they subtracted the stellar continuum using different stellar model templates from Tremonti et al. (2004), and fitted \([\text{S II}]\) and the \( \text{H}_\alpha + [\text{N II}] \) composite separately. In addition, they only used the reduced \( \chi^2 \) to evaluate the spectral decomposition results. The fitting range, fixed parameters for the emission line model, stellar mass limit (i.e., \(<3 \times 10^9 M_\odot\)) and the redshift range (\( z < 0.055 \)) are also different. Excluding this one common target, we had a final sample of 40 IMBH candidates for the variability test observations.

To set up the monitoring strategy, we estimated the expected time lag between the AGN continuum and the \( \text{H}_\alpha \) emission line (\( \tau \)) based on the BLR size–luminosity relation (Bentz et al. 2013), after adopting the \( \text{H}_\alpha \) luminosity as a proxy of the continuum luminosity (Equation (4)). The estimated time lag ranges from 0.3 to 5.3 days with a median of 1.9 days. We assigned priority to the candidates with a shorter time lag since they are more likely to have a lower \( M_{\text{BH}} \).

### 3. Observation and Data Reduction

#### 3.1. Observations

For an intra-night variability test we observed 20 targets out of 40 IMBH candidates in 2020 and 2021. These targets have an expected time lag \(<2.7 \text{ days}\), and they were observable during our monitoring runs. In 2020, from January 4 to June 7,
we observed 13 targets using the 1.3 m telescope at the Michigan–Dartmouth–MIT (MDM) observatory on Kitt Peak, Arizona, USA, with the Templeton CCD, which has $1k \times 1k$ pixels with a $0^\circ 51$ pixel size and a $8^\prime 49 \times 8^\prime 49$ field of view (FOV). The remaining seven targets were observed with the 1 m telescope at the Deokheung Optical Astronomical Observatory (DOAO) in Jeollanam-do, Korea. We used a $4k \times 4k$ FLI CCD with $2 \times 2$ pixel binning, which provided a $0^\prime 46$ pixel size and a $15^\prime 8 \times 15^\prime 8$ FOV. In addition, we repeated photometry observations for these seven objects at the MDM observatory in order to obtain narrowband filter observations, which were not possible at DOAO due to the lack of narrow filters. More details of the observing facilities can be found in our on-going monitoring studies (e.g., Woo et al. 2019b).

To investigate the variability, we targeted 2–4 candidates each night and carried out repeated observations of 3–6 epochs with a $\sim 1$–2 hr cadence. Among available filters, we used two filters: one filter is selected for obtaining the continuum flux without the H$\alpha$ emission line, and the other filter is set for the H$\alpha$ emission line (see Figure 3). Table 2 lists the observational details of individual targets, which are sorted by their $M_{\text{BH}}$.

### 3.2. Data Reduction

The standard image preprocessing was carried out using the data reduction routine of the Seoul National University AGN monitoring project (SAMP; Rakshit et al. 2019; Woo et al. 2019b) as outlined below. First, we performed dark and bias image subtraction and flat-fielding using IRAF routines (Tody 1986). We then removed cosmic rays using LA-cosmic (van Dokkum 2001), and derived the astrometric solution with astrometry-net (Lang et al. 2010). Utilizing the solution, we combined the preprocessed exposures of each target using SWarp (Bertin et al. 2002) with a median combine method for a deeper single image. Finally, to match the seeing conditions of individual epochs, we performed seeing convolution with the psf tool of the Python photutils package and the convolution tool of the Python astropy package (Astropy Collaboration et al. 2013, 2018). The preprocessed images of 20 observed candidates are presented in Figure 4.

#### Table 1

| SDSS Name | Mission     | $E$ range | log $F_{\text{x-ray}}$ | Distance | log $L_{\text{x-ray}}$ | log $L_{\text{H\alpha}}$ | log $M_{\text{BH}}$ |
|-----------|-------------|-----------|------------------------|----------|------------------------|--------------------------|----------------------|
| J075953.48+232324.2 | XMM-Newton | 0.2–12    | $-11.0$ | 132 | 43.3 | 40.2 | 6.1 |
| J083736.97+245959.2 | XMM-Newton | 0.2–12    | $-13.2$ | 131 | 41.1 | 39.9 | 6.1 |
| J084344.98+354942.0 | Swift | 15–150   | $-11.0$ | 241 | 43.9 | 41.0 | 6.2 |
| J090229.38+033059.9 | Chandra | 0.3–8.0  | $-12.8$ | 124 | 41.5 | 39.9 | 6.2 |
| J094319.14+361452.1 | ROSAT | 0.1–2.4  | $-12.5$ | 102 | 41.6 | 40.2 | 6.4 |
| J110306.23+554100.0 | ROSAT | 0.1–2.4  | $-12.4$ | 217 | 42.3 | 40.2 | 6.5 |
| J110501.97+594103.6 | Chandra | 0.3–8.0  | $-11.9$ | 151 | 42.6 | 40.8 | 6.7 |
| J112301.31+470308.6 | XMM-Newton | 0.2–12  | $-14.0$ | 114 | 40.2 | 40.0 | 6.1 |
| J114612.17+202329.9 | Chandra | 0.3–8.0  | $-11.9$ | 108 | 42.2 | 40.4 | 6.4 |
| J133514.41+104110.2 | XMM-Newton | 0.2–12  | $-11.7$ | 180 | 42.9 | 40.4 | 6.7 |
| J134632.13+642325.1 | XMM-Newton | 0.2–12  | $-11.0$ | 108 | 43.2 | 40.3 | 6.3 |
| J135419.95+325547.7 | XMM-Newton | 0.2–12  | $-11.2$ | 118 | 43.0 | 40.7 | 6.8 |

**Notes.** (1) SDSS name. (2) X-ray mission name. (3) Energy range of the X-ray observation in units of keV. (4) Absorption-corrected X-ray flux in units of erg s$^{-1}$ cm$^{-2}$. (5) Distance derived from the redshift in units of Mpc. (6) Absorption-corrected X-ray luminosity in units of erg s$^{-1}$. (7) Luminosity of the H$\alpha$ broad component estimated in this study in units of erg s$^{-1}$. (8) Black hole mass estimated in this study.

* Observed in both missions XMM-Newton and Chandra.

3.3. Differential Photometry

We performed differential photometry using the preprocessed images, as we aim to detect flux variation for this study. To determine the optimal aperture size for the photometry, we utilized a star in the image brighter than the target, and determined the aperture size for obtaining the highest S/N. We employed the same aperture for all epochs, as the seeing of each image was already matched. The typical seeing was FHWM $\sim 3^\prime 3$ at DOAO and $\sim 2^\prime 8$ at MDM in 2020, and $\sim 2^\prime 2$ at MDM in 2021. We adopted an aperture size of $\sim 9^\prime$ for both MDM and DOAO data, which roughly corresponds to $3$ times the seeing size.

We measured the instrumental magnitude of each object in the FOV with SExtractor (Bertin & Arnouts 1996) and constructed the differential light curves utilizing five comparison stars. To select the nonvariable comparison stars, we first selected the 20 brightest stars in the image and performed a variability test. We calculated the magnitude difference ($\Delta$mag) by subtracting the magnitude of the first epoch from the magnitude of each epoch for individual stars. Then, we determined the error weighted average and standard deviation of $\Delta$mag. Based on this calculation, we excluded the stars whose $\Delta$mag is larger than the average by more than a factor of two of the standard deviation. After that we tested each case by randomly selecting five stars from the remaining comparison...
Figure 3. Response function of the selected filters. As an example, the SDSS spectrum of ID1 is plotted (black) along with the kp1494 filter for obtaining the continuum flux (blue) and the kp1517 filter for Hα. The response function of three additional filters (kp1496, kp1497, and kp1498) are also presented. Note that depending on the redshift of each target, we used a different set of filters.

Table 2
Observation Information of the Observed Sample

| ID  | NSAID | R.A.  | Decl. | z    | Filter_cont | Filter_Hα | Date (yy.mm.dd) | Exp_time (cont/Hα) | # epoch (cont/Hα) | Observatory | Reference |
|-----|-------|-------|-------|------|-------------|-----------|-----------------|--------------------|------------------|-------------|-----------|
| 1   | 10779 | 09:06:13.8 | +56:10:15.2 | 0.047 | kp1494      | kp1517    | 20.01.08         | 600/600            | 4/4              | MDM        | This study |
| 3   | 33430 | 08:07:07.2 | +36:14:00.5 | 0.032 | kp1494      | kp1497    | 20.01.04         | 600/600            | 5/5              | MDM        | This study |
| 4   | 17134 | 09:55:40.5 | +05:02:36.7 | 0.034 | kp1494      | kp1497    | 20.01.08         | 600/600            | 3/3              | MDM        | This study |
| 5*  | 33232 | 13:08:41.7 | +52:46:27.4 | 0.024 | V          | R         | 20.05.13         | 840/840            | 4/4              | DOAO       | This study |
| 8   | 116134| 09:14:24.8 | +11:56:25.6 | 0.031 | kp1494      | kp1497    | 20.01.08         | 600/600            | 4/4              | MDM        | This study |
| 9*  | 45989 | 16:29:38.4 | +38:41:39.3 | 0.036 | V          | R         | 20.06.01         | 840/840            | 5/5              | DOAO       | This study |
| 11  | 59182 | 10:29:11.5 | +39:06:53.6 | 0.026 | kp1494      | kp1496    | 20.01.08         | 600/600            | 4/4              | MDM        | This study |
| 14* | 125613| 16:24:51.3 | +19:25:35.7 | 0.036 | V          | R         | 20.06.01         | 840/840            | 5/5              | DOAO       | This study |
| 20  | 15709 | 08:04:31.1 | +40:12:21.8 | 0.040 | kp1494      | kp1498    | 20.01.04         | 600/600            | 6/6              | MDM        | This study |
| 23  | 9576  | 08:01:42.6 | +42:00:19.5 | 0.032 | kp1494      | kp1497    | 20.01.04         | 600/600            | 6/6              | MDM        | This study |
| 27  | 125318| 09:54:18.2 | +47:17:25.2 | 0.033 | V          | kp1497    | 20.02.15         | 360/1200           | 5/5              | MDM        | RGG       |
| 29* | 18913 | 15:34:25.6 | +04:08:06.7 | 0.040 | V          | R         | 20.06.07         | 840/840            | 3/3              | DOAO       | RGG       |
| 30  | 109016| 10:14:40.2 | +19:24:49.0 | 0.029 | V          | kp1496    | 20.03.04         | 360/1200           | 4/4              | MDM        | RGG       |
| 31  | 12793 | 10:51:00.7 | +65:59:40.5 | 0.033 | V          | kp1497    | 20.03.04         | 360/1200           | 4/4              | MDM        | RGG       |
| 32  | 91579 | 12:03:25.7 | +33:08:46.2 | 0.035 | V          | kp1497    | 20.03.04         | 360/1200           | 5/5              | MDM        | RGG       |
| 34* | 99052 | 16:05:31.9 | +17:48:26.2 | 0.032 | V          | R         | 20.06.07         | 840/840            | 3/3              | DOAO       | RGG       |
| 35  | 112250| 11:23:15.8 | +24:02:05.2 | 0.025 | V          | kp1496    | 20.03.04         | 360/1200           | 4/4              | MDM        | RGG       |
| 36  | 47066 | 08:51:25.8 | +39:35:41.8 | 0.041 | V          | kp1498    | 20.02.15         | 360/1200           | 5/5              | MDM        | RGG       |
| 38* | 104565| 13:43:32.1 | +25:31:57.7 | 0.029 | V          | R         | 20.05.13         | 840/840            | 4/4              | DOAO       | RGG       |
| 40* | 79874 | 15:26:37.4 | +06:59:41.7 | 0.038 | V          | R         | 20.06.07         | 840/840            | 3/3              | DOAO       | RGG       |

Notes. (1) Identification number assigned in this study. (2) NASA—Sloan Atlas identification number. (3) R.A. in J2000.0. (4) Decl. in J2000.0. (5) Redshift. (6) Filter for the continuum observation. (7) Filter for the Hα observation. (8) Observation date. (9) Exposure time in units of s for the continuum and Hα observations. (10) The number of epochs for the continuum and Hα observations. (11) Observation site. (12) Name of the original sample. This study: IMBH candidates identified in this study. RGG: IMBH candidates selected from Reines et al. (2013).

* Targets observed at both observatories.

Stars and picked a set of five stars whose standard deviation of their Δmag is the smallest. To estimate the uncertainty of the calibrated magnitude in the light curves, we combined the measurement error (σ_m) and the standard deviation of the Δmag of the selected five comparison stars (σ_v) in quadrature:

\[ σ = \sqrt{σ_m^2 + σ_v^2}. \]

The calibrated light curves from differential photometry are presented in Figure 5.

4. Results and Analysis

4.1. Variability Amplitude

To investigate the variability of the observed IMBH candidates, we calculated three different parameters, namely, the flux ratio between the maximum and minimum brightness (R_{max}), standard deviation of the magnitudes in the light curve (RMS), and the normalized excess variance of the flux (F_{var}) defined as

\[ F_{var} = \frac{\sigma^2 - f_{avg}^2}{f_{avg}}. \]
where $f_{\text{avg}}$ is the average of the flux of the target, $f_{\sigma}$ is the standard deviation of the flux, and $f_{\delta}$ is the average of the flux uncertainty at each epoch (Rodríguez-Pascual et al. 1997, Walsh et al. 2009). These measurements of the variability amplitude are presented in Table 3. Note that $F_{\text{var}}$ is often considered to be the most reliable parameter of variability because it accounts for the uncertainty of the flux measurement.

We examined the variability of the AGN continuum and H$\alpha$ emission line using the two light curves presented in Section 3. Note that the flux in the H$\alpha$ light curve, which was measured

Figure 4. Images of the 20 candidates observed with the H$\alpha$ focused filter (see Table 2). North is up and the east is to the left. The 5″, 10″, and 15″ apertures are denoted with cyan circles. The ID assigned in this study is shown in the upper left corner of each panel.
with the adopted narrow- or broadband filter, contains H\(\alpha\) emission line flux as well as AGN continuum and a nonvariable host galaxy contribution. In the case of the continuum light curve, the measured flux is the sum of the flux mainly from the AGN continuum and host galaxy (see Figure 3). Thus, the measured variability amplitude depends on the dominance of the AGN component over the host galaxy flux. In other words, even if an AGN is highly variable, a nonvariable host galaxy contribution may dilute the flux variability in the light curve.

The measured \(R_{\text{max}}\) in the continuum light curve ranges from 1.01 to 1.33, indicating that the maximum intra-night variability is over 0.3 mag, while the highest and the median value of RMS are 0.13 mag and 0.01 mag, respectively. The largest RMS is similar to the median RMS ~0.14 mag of typical Seyfert 1 galaxies (Rakshit & Stalin 2017). However, several targets in the sample show very weak variability, leading to a relatively low median RMS. If we assume that the measurement error is ~1\%, continuum flux variability is detected for all targets, with a typical RMS variability of \(\lesssim 0.01\) mag. Considering the measurement uncertainty of individual targets, we identified nine candidates (namely, IDs 5, 27, 29, 30, 32, 35, 36, 38, and 40) as more secure variable targets with a measurable \(F_{\text{var}}\) of ~0.01–0.05 mag, which suggests that the detected variability is a few percent. The other 11 targets have no measurable \(F_{\text{var}}\) value, which may be caused by a relatively large measurement error compared to the intrinsic variability, dilution due to the dominance of the nonvariable host galaxy flux, or the lack of intrinsic AGN variability.

In comparison, the measured \(R_{\text{max}}\) in the H\(\alpha\) light curve ranges from 1.01 to 1.16, while RMS shows a narrower range of ~0.01–0.06 mag than that of the continuum light curve. The median values of \(R_{\text{max}}\), RMS, and \(F_{\text{var}}\) are 1.04, 0.02 mag, and 0.01 mag, respectively, which is similar to the median values from the continuum light curve. Their highest values are 1.16, 0.06 mag, and 0.02 mag, respectively, showing that the variability of H\(\alpha\) is less significant than for the continuum. As all targets except for ID 31 show RMS \(\gtrsim 0.01\) mag, the variability of H\(\alpha\) seems to be detected for most targets.

Figure 4. (Continued.)
However, after considering the measurement error, we only obtained an excess variance for four targets (namely, IDs 1, 5, 23, and 30) with $F_{\text{var}} \sim 0.01$–0.02 mag.

To better understand the measured variability amplitude in the H$\alpha$ light curve, we performed a spectral analysis to measure the fraction of the broad H$\alpha$ component in the total flux obtained through each filter. By multiplying the response function of the used filter with the SDSS spectrum of each object, we calculated the fraction of the broad H$\alpha$. Note that the calculated fraction is an upper limit since the adopted aperture of $\sim 9''$ in the photometry is much larger than the $\sim 3''$ fiber used for the SDSS spectra. For the broad R filter, the fraction of the broad H$\alpha$ is insignificant ($\leq 1\%$), indicating that the detection of the H$\alpha$ variability is very challenging even if the broad H$\alpha$ emission line intrinsically varies by $< 100\%$. By contrast, the broad H$\alpha$ fraction in the narrow filter is significantly larger ($2\%$–$24\%$; see last column in Table 3), which is much larger than the measurement uncertainty of $1\%$. Thus, if the intrinsic variability is significant, it is likely that the variability of H$\alpha$ is detected in the narrow filter based light curves.

For example, IDs 1, 5, 23, and 30 from MDM observations have a considerable H$\alpha$ fraction (14.1%, 1.9%, 4.5%, and 3.5%), and the excess variance is also detected as $F_{\text{var}} \sim 1\%$–2%. Other targets with no detection of excess variance may have a very small flux ratio of the H$\alpha$ emission or weak variability. Note that for ID 1 and ID 23, we obtained no excess variance $F_{\text{var}}$ in the continuum light curve, which is likely due to the fact that a nonvariable host galaxy component is dominant in the continuum light curve, or that the continuum flux variability amplitude is smaller than the measurement error.

By contrast, the targets observed with the broad R filter (namely, IDs 9, 14, 29, 34, 38, and 40) have no measurable $F_{\text{var}}$ value due to the insignificant H$\alpha$ fraction. The dominant continuum may have diluted the intrinsic H$\alpha$ variability, if there were any. In the case of ID 5, observed with a broad R filter, we obtained a somewhat unexpected result. Since the fraction of H$\alpha$ is less than 0.1% of the total flux measured with photometry, the 1% excess variance seems too high to be detected because the H$\alpha$ flux would need to vary by a factor of $> 10$. Note that its AGN continuum variability is negligible, as we detect no excess variance in the continuum light curve. We consider a possibility that the measurement error in the H$\alpha$ light curve is underestimated and smaller than that of the continuum light curve.

In summary, we detected RMS variability for all 20 targets, and obtained excess variance $F_{\text{var}}$ for nine targets based on the observed intra-night continuum light curves. In the case of the H$\alpha$ light curves, we determined an RMS variability of $\geq 1\%$ for all targets except for ID 31, and reliable excess variance for four targets. Only two candidate, IDs 5 and 30, showed a reliable excess variance $F_{\text{var}}$ in the light curve of both the continuum and H$\alpha$, suggesting that they are the best IMBH candidates in the sample. The other nine targets, namely, IDs 1, 23, 27, 29, 32, 35, 36, 38, and 40, are also good candidates for

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**Figure 5.** Continuum (blue) and H$\alpha$ (red) light curves of the 20 candidates. The total error (thin line) is composed of the measurement error (thick line) and the systematic error from differential photometry. Note that for the H$\alpha$ light curves, we only present the photometry results from narrowband filters. The ID assigned in this work is shown in the upper left corner of the panel.
further studies since they showed excess variance either in the continuum or in the Hα light curve.

4.2. Variability versus AGN Properties

We compared the AGN properties and $\text{RMS}_{\text{H}α}$, measured from the narrow filter based light curves (see Figure 6). We computed a least-squares linear regression for the highly variable candidates identified in the previous section using the `linregress` tool of the Python `scipy` package (Virtanen et al. 2020). The variability amplitude shows a weak positive correlation with $M_{\text{BH}}$ and $\sigma_{\text{H}α}$, whose correlation coefficients ($r$-values) are 0.19 and 0.24, and whose two-sided $p$-values for a null hypothesis of no correlation are 0.58 and 0.48, respectively. By contrast, $L_{\text{H}α}$ is anticorrelated with $\text{RMS}_{\text{H}α}$, having weak correlation coefficients ($r$-value $= -0.14$ and $p$-value $= 0.67$). Similar results have been found by Rakshit & Stalin (2017), who reported that the variability strength has an anticorrelation with AGN luminosity, but a correlation with $M_{\text{BH}}$ and the velocity dispersion of the broad permitted lines. The correlation of their sample at $z < 0.2$ is not significant (i.e., $p$-value $> 0.1$), suggesting that our result is not inconsistent with that of Rakshit & Stalin (2017). However, the time baseline and the number of epochs are clearly limited, and further studies with sufficient data are required to unveil the nature of the variability correlation of IMBH candidates.

5. Discussion

Several previous studies searched for low-mass BHs hosted in dwarf galaxies by detecting the spectral signature of BH accretion using the SDSS galaxy sample and identified IMBH candidates with a broad Hα emission line (e.g., Reines et al. 2013; Baldassare et al. 2015; Eun et al. 2017; Chilingarian et al. 2018). We compared the selection criteria and the results of the previous works with this study. For example, Eun et al. (2017) found 611 broad Hα candidates from SDSS DR7 data. Their mean value of Hα luminosity ($10^{40.7_{-0.3}^{+0.3}}$ erg s$^{-1}$) is larger than the mean value of our sample of 131 objects with a broad Hα ($10^{40.3}$ erg s$^{-1}$). The velocity dispersion of Hα of most of their targets is also larger than 1000 km s$^{-1}$ (see Figure 10 in Eun et al. 2017), while $\sim 70\%$ of our broad Hα candidates (92/131) have $\sigma_{\text{H}α}$ smaller than 1000 km s$^{-1}$. Consequently, the estimated $M_{\text{BH}}$ of the sample in Eun et al. (2017) is larger than $10^6 M_\odot$. By contrast, we have found 25 targets whose estimated $M_{\text{BH}}$ is less than $10^6 M_\odot$. Note that Eun et al. (2017) conservatively selected clear type 1 AGN candidates in order to avoid false detections, whereas we set a lower $\sigma_{\text{H}α}$ cut for the definition of the type 1 AGN, and performed a more delicate spectral analysis using $\chi^2$ and the BIC to find targets with a weak Hα broad component.

A similar comparison can be done with the broad Hα candidates from Reines et al. (2013). They have identified
candidates with a dimmer Hα broad component than ours, as their mean \( L_{\text{H}\alpha} \left( 10^{39.7} \text{ erg s}^{-1} \right) \) is lower than that of our 131 broad Hα candidates (10^{40.3} \text{ erg s}^{-1}). Also, their mean \( \sigma_{\text{H}\alpha} \) (~670 km s^{-1}) is lower than ours (~870 km s^{-1}). The main difference comes from the fact that they only surveyed dwarf galaxies at \( z < 0.055 \), by imposing a stellar mass limit, \(< 3 \times 10^9 \text{ M}_\odot \). Since we searched for more distant targets, it is likely that we missed the candidates having a weak Hα broad component at \( z > 0.055 \). Note that among the 25 IMBH candidates in this study whose \( M_{\text{BH}} \) is less than \( 10^9 \text{ M}_\odot \), only one target overlaps with the IMBH candidates in Reines et al. (2013). While both samples were selected from the SDSS catalog based on similar selection criteria, the details of the selection scheme and the spectral decomposition analysis caused the difference. It shows that more missing IMBH candidates can be identified among SDSS galaxies by refining the selection procedures.

Chilingarian et al. (2018) also performed a similar study to identify IMBHs among SDSS galaxies. They reported IMBH candidates whose estimated \( M_{\text{BH}} \) is less than \( 10^8 \text{ M}_\odot \), based on their own nonparametric emission line fitting method along with an X-ray flux analysis (Chilingarian et al. 2017). While it is possible that, for some of the candidates, their fitting method of constructing multiple template sets of flux-normalized Gaussians may suffer from an overfitting problem, underestimating the luminosity and velocity dispersion of the broad Hα component, they demonstrated that a spectral analysis can be utilized to find IMBH candidates even with \( M_{\text{BH}} \sim 10^8 \text{ M}_\odot \).

The presence of a broad Hα may not be sufficient to qualify a galaxy as a type 1 AGN since the line width of Hα of IMBH candidates is relatively narrow compared to the conventional limit of \( \sim 1000 \text{ km s}^{-1} \), and other sources such as supernovae are able to exhibit a broad Hα (e.g., Izotov et al. 2007; Izotov & Thuan 2009a; Graur & Maoz 2013). However, by detecting variability, these targets can be confirmed as mass-accreting IMBHs. While various studies performed a variability analysis over a relatively long timescale to identify IMBH candidates (e.g., Baldassare et al. 2018; Martínez-Palomera et al. 2020), short-timescale, i.e., intra-night variability studies are rare. We compare our results with the intra-night variability analysis conducted by Kim et al. (2018), who monitored AGN candidates in the SMBH regime. While the FOV (\( \sim 10' \times 10' \)) of our photometric observations is much smaller and the time baseline is shorter (i.e., \( \sim 8 \) hr) than those of Kim et al. (2018), we obtained measurable variability amplitudes for a subsample of the IMBH candidates, suggesting that it is possible to detect variability of IMBH candidates using intra-night monitoring programs with a relatively short cadence. Future narrowband monitoring programs with well-defined strategies for the time baseline and cadence can provide a valuable assessment and confirmation of IMBH candidates.

### 6. Summary and Conclusion

To detect the accretion signature of IMBH candidates, we identified galaxies with a broad Hα emission line and performed an additional analysis to constrain the nature of these targets. The main results are summarized as follows.

1. We performed spectral analysis of the Hα emission line region using a large sample of the SDSS DR7 galaxies, and have found 131 new targets with a weak broad Hα line. Among them, 25 targets have \( M_{\text{BH}} \) less than \( 10^6 \text{ M}_\odot \).
2. To find additional evidence of AGN activity, we obtained X-ray data and measured the X-ray luminosity of 19 candidates. However, the estimated \( M_{\text{BH}} \) of these targets is larger than \( 10^6 \text{ M}_\odot \).
3. We observed 20 IMBH candidates for an intra-night variability test and reported 11 objects with the largest variability amplitude as the best IMBH candidates.

Our study demonstrates that an intensive monitoring campaign with a larger-aperture telescope along with a narrowband filter can provide strong constraints of the population of IMBHs at low \( z \) by overcoming the relatively large measurement error and the limited number of epochs of this study. The best IMBH candidates obtained in this study are among the most suitable targets for further studies, i.e., spectroscopic reverberation mapping, to confirm them as IMBHs and to determine reliable BH masses.

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### Appendix

We present the spectral decomposition results of the 24 broad Hα candidates with \( M_{\text{BH}} < 10^6 \text{ M}_\odot \) in Figure 7. The result for candidate 1 is shown in Figure 1. As explained in Section 2.2.1, IDs 2, 12, 14, 16, 20, 23, and 24 show the case in which the model without an Hα broad component (second and
Figure 7. Spectral decomposition of the 24 broad Hα candidates whose estimated $M_{\text{BH}}$ is smaller than $10^6 M_\odot$. The first and third columns show the best-fit model with an Hα broad component for each emission line region. The second and forth columns show the best-fit model without an Hα broad component. The stellar continuum subtracted spectrum is plotted in black, and the blue line shows the best-fit model composed of narrow Gaussian components (magenta) and an Hα broad component (red). At the bottom of each panel, the residuals between the spectrum and the best-fit model are plotted in black.
forth column) cannot fit the H\(\alpha\) line well and a large residual is present between each emission line. The model without an H\(\alpha\) broad component for IDs 3, 5, and 17 is not able to fit the both the H\(\alpha\) and [S II] lines, and the model for the other candidates cannot fit the [S II] lines appropriately. The model [S II] lines are broader than in reality, so a significant residual is shown.
between the two [S II] lines. The amplitude of the Hα broad component for IDs 6, 12, 14, and 20 seems low relative to the amplitude of the emission lines. However, their absolute amplitude is larger than their flux density error and the residual around the emission lines, so adding the Hα broad component is reliable. Also note that, according the criteria of Section 2.2.1,
the BIC and $\chi^2_{\text{red}}$ of their fitting results decrease by 10 when the broad component is added, and the A/N of each broad component is larger than 10.

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