SUPERMASSIVE BLACK HOLES WITH HIGH ACCRETION RATES IN ACTIVE GALACTIC NUCLEI. III. DETECTION OF FeII REVERBERATION IN NINE NARROW-LINE SEYFERT 1 GALAXIES

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ABSTRACT

This is the third in a series of papers reporting on a large reverberation-mapping campaign aimed to study the properties of active galactic nuclei (AGNs) with high accretion rates. We present new results on the variability of the optical FeII emission lines in 10 AGNs observed by the Yunnan Observatory 2.4 m telescope from 2012 to 2013. We detect statistically significant time lags, relative to the AGN continuum, in nine of the sources. This accurate measurement is achieved using a sophisticated spectral fitting scheme that allows for apparent flux variations of the host galaxy, and several narrow lines, due to the changing observing conditions. Six of the newly detected lags are indistinguishable from the Hβ lags measured in the same sources. Two are significantly longer and one is slightly shorter. Combining these findings with the FeII lags reported in previous studies, we find an FeII radius–luminosity relationship similar to the one for Hβ, although our sample by itself shows no clear correlation. The results support the idea that FeII emission lines originate in photoionized gas, which, for the majority of the newly reported objects, is indistinguishable from the Hβ-emitting gas. We also present a tentative correlation between the lag and intensity of FeII and Hβ and comment on its possible origin.

Key words: galaxies: active – galaxies: nuclei – galaxies: Seyfert – methods: data analysis – quasars: emission lines

1. INTRODUCTION

Most active galactic nuclei (AGNs) show prominent FeII emission lines in their spectra. The lines appear in several broad bands that represent thousands of individual transitions. The stronger bands cover the ranges of 4000–5400 Å (hereafter optical FeII lines), 2800–3500 Å, and 2000–2600 Å (hereafter UV FeII lines; e.g., Wills et al. 1985; Sulentic et al. 2000; Hu et al. 2008 and references therein). The strongest FeII lines (relative to Hβ) are observed in narrow-line Seyfert 1 galaxies (NLS1s see, e.g., Osterbrock & Pogge 1985; Boller et al. 1996). Such objects are characterized by (1) narrow (< 2000 km s<sup>−1</sup>) broad emission lines, (2) weak [O III] lines, and (3) steep hard X-ray spectra. These objects are usually found at the extreme end of the so-called Eigenvector 1 sequence (Boroson & Green 1992; Sulentic et al. 2000; Shen & Ho 2014), indicating high Eddington ratios and several other properties that are not fully understood.

Some NLS1s show evidence of super-Eddington accretion, with <i>L</i><sub>bol</i><i>/L</i><sub>Edd</sub> > 1. We refer to these objects as super-Eddington accreting massive black holes (SEAMBHs). Our earlier work (Wang et al. 2013, 2014) shows that such objects are potentially a new kind of standard candle for cosmology. To test this idea, and to study the physical properties of extreme NLS1s in more detail, we have initiated a large reverberation-mapping (RM) campaign to accurately measure the black hole (BH) mass of such sources. The initial results of this campaign have been published in Du et al. (2014, hereafter Paper I) and Wang et al. (2014, Paper II). This paper, the third in this series, is dedicated to the study of FeII emission lines in our sample of SEAMBH candidates. A fourth paper, submitted in parallel to this one, presents new data on Hβ time lags and BH mass in five extreme SEAMBHs and focuses on the modification of the <i>R</i><sub>BLR</i>–<i>L</i> relationship in AGNs (e.g., Kaspi et al. 2000, 2005; Bentz et al. 2013) in the presence of such sources.

The excitation mechanism of the FeII emission in AGNs has been discussed in numerous publications (e.g., Collin-Souffrin et al. 1980; Netzer & Wills 1983; Joly 1987; Sigut & Pradhan 1998; Baldwin et al. 2004, Ferland et al. 2009). Most of these studies suggest an origin in the broad-line region (BLR), but the line intensities calculated so far are in poor agreement with most observations. Other suggestions connect these lines to the outer part of the central accretion disk (e.g., Joly 1987), but the agreement with the observations is still poor. In particular, none of the existing models can satisfactorily explain the relative intensity of the UV and optical FeII lines and the observed FeII spectrum in the range of 2000–2600 Å. Line variability is an important tool in such studies because it can indicate, given a measured time lag relative to the continuum variations, the location of the FeII-emitting gas. Such variations have been detected in a number of sources (e.g., Boksenberg & Netzer 1977; Maoz et al. 1993; Kollatschny et al. 2000; Vestergaard & Peterson 2005; Wang et al. 2005; Kuehn et al. 2008; Shapovalova et al. 2012), but robust lag measurements were not obtained. This situation has recently changed. Bian et al. (2010) revisited the data on PG 1700+518 from Kaspi et al. (2000) and measured the light
curves of the optical Fe II lines. They found a significant time lag relative to the 5100 Å continuum, albeit with a very large uncertainty. Rafter et al. (2013) and Chelouche et al. (2014) adopted the multivariate correlation function (MCF) scheme of Chelouche & Zucker (2013), which was designed for photometric RM. Rafter et al. (2013) studied the NLS1 SDSS J13913.91+33555.1 using RM and found that the Fe II time lag is consistent with that of the Hβ line. Chelouche & Zucker (2013) measured optical Fe II light curves and time lags for three of the objects in Kaspi et al. (2000), one of which is the object studied by Bian et al. (2010). They also find a somewhat less significant Fe II time lag for three other sources. Chelouche & Zucker (2013) present a tentative Fe II size–luminosity relation and suggest that the Fe II emission-region size is comparable to that of the Hβ line. Barth et al. (2013) used spectroscopic measurements of optical Fe II lines and found lags that are 1.5 and 1.9 times longer than the corresponding Hβ. All these studies confirm the photoionization origin of the Fe II lines. The success of the Barth et al. (2013) campaign is due both to the detailed and frequent spectroscopic observations, and a novel method they used to correct for the host galaxy’s contribution to the optical spectra.

This paper presents the results obtained from our measurements of the time lags of the optical Fe II lines (hereafter Fe II lines) in our SEAMBH campaign. We have attempted to detect such lags in 10 of the sources and were able to obtain statistically significant results in nine of them. In six of the newly measured sources, the Fe II lag is entirely consistent with the Hβ lag, and in two others, it is considerably longer. Section 2 gives a brief review of the observations and data reduction. Section 3 describes our spectral fitting method, with emphasis on host galaxy and narrow-line subtraction, which we find to be crucial to the analysis. More details are given in Appendix A. Section 4 presents Fe II light curves and their analysis for both Fe II and H β, and compares the results of the new H β lags to those presented in Paper I and Paper II. In Section 5, we plot the size–luminosity relation for Fe II and compare the lag and intensity of Fe II with H β. The implications and an additional interpretation are also provided. Section 6 gives a summary of the new results.

2. OBSERVATIONS AND DATA REDUCTIONS

The details of the SEAMBH campaign, including the observations, data reduction, and analysis, were presented in Paper I and Paper II. For completeness, we summarize the more important points below and discuss in detail the new method of galaxy and narrow-line subtraction.

2.1. Sample

We observed 10 NLS1s identified as SEAMBH candidates, spectroscopically and photometrically, between 2012 October and 2013 June. Object names and coordinates are listed in Table 1 of Paper II. H β time lags for three of the sources (Mrk 335, Mrk 142, IRAS F12397+3333) are presented in Paper I, and for five additional sources (Mrk 1044, Mrk 382, MCG +06–26–012, Mrk 486, Mrk 493) in Paper II. Like many other NLS1s (e.g., Boroson & Green 1992; Sulentic et al. 2000; Boroson 2002; Zhou et al. 2006), all the sources in our sample show strong Fe II emission lines and high \( L_{\text{bol}}/L_{Edd} \). This sample is therefore different from most AGNs in the local universe, and none of the results presented below should be compared with earlier studies, like Hu et al. (2008), that address the general population properties.

2.2. Spectroscopy and Data Reduction

The spectra were obtained using the Yunnan Faint Object Spectrograph and Camera, which was mounted on the Lijiang 2.4 m telescope at the Yunnan Observatory of the Chinese Academy of Sciences. A long slit with a projected width of 2″5 was oriented to take the spectra of the object and a nearby non-varying comparison star simultaneously, following, e.g., Maoz et al. (1990) and Kaspi et al. (2000). The comparison star was then used as a standard for flux calibration. For the Lijiang 2.4 m telescope, the rotator is accurate and the tracking is stable. Thus, the object and the comparison star were kept within the slit during the typical 30 minute exposures. The distance between the object and the comparison star along the direction of the slit width is less than 1 pixel (0″283).

Grism 14 was used and yielded spectra covering the wavelength range of 3800–7200 Å, with a dispersion of 1.8 Å pixel \(^{-1}\). The final spectral resolution, obtained by comparing the width of the [O III] emission line with the one measured from the Sloan Digital Sky Survey (SDSS; York et al. 2000) spectrum of the same object, is roughly 500 km s \(^{-1}\). All spectra are extracted in a uniform, large aperture of 8″5 to minimize light loss. The flux calibration is based on a comparison of the object flux to the comparison star flux in the 2″5 × 8″5 apertures. However, the host galaxy flux calibration is different because of the non-stellar image—the galaxy is extended and resolved. This can result in apparent flux variations due to variable seeing and mis-centering. This requires a different calibration procedure that has a large impact on the various light curves. Appendix A details this procedure.

3. LINE AND CONTINUUM MEASUREMENTS

3.1. Fitting Scheme

The traditional method for measuring the flux of the continuum and the broad emission lines, in most RM studies, is simple integration (e.g., Kaspi et al. 2000). A straight line is set between two line-free windows to define the AGN continuum, and the flux of the emission line is measured using a simple integration above the line. This method works well for single, strong emission lines, e.g., H β, because there are no (or only weak) other emission lines in this range and the wavelength window is narrow enough for the continuum to be approximated by a straight line. In the case of Fe II, neither condition is satisfied.

Fe II emission consists of thousands of lines that form a pseudo-continuum. The most prominent features in the optical band are two bumps between 4500 and 5500 Å: one between H β and H ν, and the other on the red side of [O III] \( \lambda 5007 \). Even for quasars, whose host galaxies are extremely faint relative to AGNs, it is hard to find “pure” continuum windows, and it is inappropriate to assume a straight line over such a wide wavelength range of more than 1000 Å. The strong host galaxy contribution in most of our objects, and the contamination by other emission lines (e.g., He II and coronal lines), makes the situation much worse. Appendix B presents the Fe II light curves that were measured by the traditional integration method. All light curves have a large scatter, and only less than half show rough structures. A simultaneous fitting that
includes the Fe II emission and all the other spectral components is necessary.

Template-fitting is a widely used method for measuring Fe II emission in single-epoch spectra of AGNs (see, e.g., Hu et al. 2008 for a brief overview). Input–output simulations show that template-fitting is a reliable measurement of Fe II emission with an equivalent width (EW) > 25 Å in quasars (Hu et al. 2008). It is also common to include a host galaxy component into the fitting of Type I AGNs with strong host contribution (e.g., Zhou et al. 2006; Ho & Kim 2009). This method has recently been adopted to measure the light curves in a few RM studies, proving to be successful. Bian et al. (2010) reanalyzed the spectra of PG 1700+518 using data from Kaspi et al. (2000). They detected a lag of 209±100 days for Fe II emission. Barth et al. (2013) performed a very careful spectral decomposition including a power law continuum, a host galaxy component, an Fe II template, and other emission lines (Hβ, [OIII], He II, and He I). Using this technique they were able to obtain statistically significant reverberation lags of the Fe II lines in two Seyfert 1 galaxies, NGC 4593 and Mrk 1511.

The spectral fitting in this paper follows the algorithm of Hu et al. (2012), where several spectral components are fitted simultaneously by minimizing the χ² via the Levenberg–Marquardt method. All the light curves are obtained directly from the results of the fitting. Before fitting, we correct the calibrated spectra for Galactic extinction and redshift. We use the RV-dependent Galactic extinction law given by Cardelli et al. (1989) and O'Donnell (1994), and RV is assumed to be 3.1. The redshift z and V-band extinction are taken from the NASA/IPAC Extragalactic Database⁸ and Schlafly & Finkbeiner (2011), as listed in Papers I and II.

The left panel of Figure 1 shows the fitting to the spectrum of Mrk 382 taken at Julian date (JD) 2456298, after Galactic extinction and redshift correction. The fitting is performed in the rest frame wavelength range 4150–6280 Å, except two narrow windows around Hγ and He I λ5876. The two lines are not blended with the major part of Fe II emission, and their study is beyond the scope of this paper. We keep them out of the fitting to avoid introducing too many unnecessary parameters. The observed spectra in the fitting windows are plotted in green, while those left out of the fitting are in black. The fitting includes the following components: (1) a single power law, (2) Fe II emission, and (3) the host galaxy. These three components, which when combined together form the pseudo-continuum,⁹ are plotted in blue. (4) The fitting also includes the Hβ emission line plotted in magenta; (5) the broad He II λ4686 emission line plotted in cyan; and (6) the narrow emission lines plotted in orange, including [O III] λλ4959, 5007, He II λ4686, He I λ4471, and several coronal lines. The summed model is plotted in red. The bottom panel shows the residual spectrum. Note that, although He I λ4876 is not in the fitting window, its profile is well recovered after removing the [N I] λλ5890, 5896 (Na D) absorption lines from the host galaxy.

Limited by the signal-to-noise ratio (S/N) for the individual-night spectra, there are degeneracies between several pairs of spectral components, including: (a) the AGN power-law continuum and the host galaxy, (b) Fe II emission and the broad He II line, and (c) Fe II emission and the coronal lines. Thus, we first fit the high-S/N mean spectrum with all parameters set free. We then fit each individual-night spectrum with the values of some parameters fixed to those obtained from the fitting of the mean spectrum. The details of each

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⁸ http://ned.ipac.caltech.edu/

⁹ Note that the pseudo-continuum here is not defined in the ordinary way, in which the host galaxy component is not included.
spectral component, and the fitting parameters, are described in the following subsections.

3.1.1. AGN Power-law Continuum

A single power law is used to describe the featureless AGN continuum. It has two parameters: the flux density at 5100 Å ($F_{\text{AGN}}$), and the spectral index ($\alpha$, defined as $f_{\lambda} \propto \lambda^{-\alpha}$). There is some degeneracy between the power-law continuum and the host galaxy. A larger $\alpha$ or a higher-flux galaxy ($F_{\text{gal}}$) both make the total spectrum redder (note that the unphysical change in the color of the observed spectrum caused by weather or differential atmospheric refraction is avoided in our observation, as our flux calibration by the comparison star provides differential spectrophotometry in each wavelength bin of the spectrum; see Section 2.2).

For our observations, we find that the relative flux of the galaxy component is the main reason for the change in the total spectrum slope. Figure 1 illustrates this point. The right panel shows the spectrum of Mrk 382 taken at JD 2456299, just one day after the date of the spectrum shown in the left panel. Apparently, the flux at 5100 Å is ~30% higher than the day before, and the color is redder. However, the difference between the V-band magnitudes of the two nights is only ~0.01 mag. We have therefore adopted an approach based on the assumption that the absolute flux of the host must be constant, but the relative flux inside the slit can vary depending on the observing conditions. This is illustrated in detail in Appendix A. The conclusion about the AGN continuum is in line with several, but not all, studies discussing the relation between $\alpha$ and luminosity in AGNs. Most recently, Zhang (2013) investigated this issue using the RM data of the 17 quasars from Kaspi et al. (2000). They found no strong dependence of $\alpha$ on the variability of the luminosity. Thus, in the fitting of each individual-night spectrum, we fix the value of $\alpha$ to agree with the best fit to the mean spectrum, and leave $F_{\text{AGN}}$ and $F_{\text{gal}}$ free. Comparing the left and right panels of Figure 1, only the galaxy component changes. In this way, the resulting $F_{\text{AGN}}$ light curve matches the V-band light curve well (see Appendix A). Our fitting is consistent with no changes in the spectral index as a function of luminosity.

3.1.2. Fe II Emission

There are several optical Fe II templates available in the literature. Among them, two templates, from Boroson & Green (1992) and Véron-Cetty et al. (2004), are most widely used, both constructed from the spectrum of the NLS1 galaxy I Zw 1. Barth et al. (2013) find that the template from Véron-Cetty et al. (2004) yields inconsistent He I emission lines; significant broad He I λ4922 and λ5016 emission lines are needed while He I λ4471 is constrained to have zero flux by the fitting. We compared these two templates and found that the one from Boroson & Green (1992) gives a better fitting, as judged by the smaller reduced $\chi^2$. No broad He I λ4922 and λ5016 emission lines are needed, which is consistent with the zero flux of He I λ4471. Introducing the two broad He I lines will add parameters to the fit and will introduce additional degeneracy between He I λ4922 and H β. Given this, we chose the Fe II template from Boroson & Green (1992) in this paper.

The Fe II template is convolved with a Gaussian function to be scaled, broadened, and shifted (see Hu et al. 2008 for details). Three parameters, the flux ($F_{\text{Fe II}}$), the full width at half-maximum (FWHM$_{\text{Fe II}}$), and shift ($V_{\text{Fe II}}$), are used for Fe II emission in the fitting. We let all the three parameters be free during the fitting of each individual-night spectrum. Note that $F_{\text{Fe II}}$ is defined as the flux of the integrated Fe II emission between 4434 and 4684 Å from the best-fit Fe II model, following Boroson & Green (1992).

3.1.3. The H β Line

The spectral resolution of our spectra is rather low ($\sim$500 km s$^{-1}$), and in addition our objects are selected to have narrow H β emission lines. Thus, it is hard to decompose the H β emission line and remove the narrow component that comes from the narrow-line region. Considering that the contribution of the narrow component is weak and supposed to be constant over reverberation timescales (Peterson et al. 2013), we treat the entire H β emission line as one component. The entire H β profile is modeled by a Gaussian–Hermite function (van der Marel & Franx 1993). All five parameters of the Gaussian–Hermite function are set free in the fitting of each individual-night spectrum. The flux of the line ($F_{\text{H β}}$) is calculated from the best-fit model.

3.1.4. Narrow Emission Lines

Besides the strong [O III] λλ4959, 5007, there are many other narrow emission lines in the wavelength range of our fit spectrum (Vanden Berk et al. 2001). We identify narrow He II λ4686, He I λ4471, and several high-ionization forbidden coronal lines. In some objects, these narrow lines are so strong that their contamination is non-negligible to the Fe II measurement. Figure 2 shows an individual-night spectrum of Mrk 335 and our fit. The strong coronal lines included in this case are [Fe II] λ5158, [Fe II] λλ5167, [N II] λλ5199, [Ca III] λλ5390, [Fe II] λ5721, and [Fe II] λλ6086. Adding these lines significantly improves the fit.

The intensities of the narrow lines differ from one object to the next. For each object, we first identify narrow lines in the mean spectrum by testing the goodness of the fit. Only lines that are identified in the mean spectrum are included in the fitting of individual-night spectra. Each narrow emission line is modeled by a Gaussian. These lines are coming from the narrow-line region and hence do not vary on the campaign timescale. Thus, we constrain them to have the same velocity width and shift as those of the [O III] λλ5007 line. The flux ratio relative to [O III] λ5007 is also kept constant, as given by the best fit to the mean spectrum (the flux ratio of [O III] λλ4959 to λλ5007 is fixed to the theoretical value of 1/3), in order to avoid the degeneracy between these lines and Fe II. Only the flux, velocity width, and shift of [O III] λλ5007 are set free.

3.1.5. Broad He II Emission Line

The broad He II λ4686 emission line is strong in the spectrum of some objects in our sample. Figure 2 shows an example. The line, plotted in cyan, is much broader than H β, and strongly blueshifted. Such a line profile is common for high-ionization lines in NLS1s and is consistent with that of the ultraviolet (UV) He II λλ1640 line in SDSS spectra (Richards et al. 2011). It is even more prominent in the rms spectra of our objects, indicating a large variability that is similar to the results in previous He II RM studies (e.g., Bentz et al. 2010; Barth et al. 2011; Grier et al. 2012).
Figure 2. Example of individual-night spectrum and model fitting for Mrk 335. The spectrum, model, and residuals are plotted in the same manner as those in Figure 1. Note the strong narrow He II and coronal lines labeled by ion and wavelength.

The broad He II line is heavily blended with Fe II emission. The high-ionization lines in AGNs are often asymmetric (Richards et al. 2011), but there are no other high-ionization lines in the wavelength range of our spectra to constrain the profile of the He II line. We first fit the line profile in the mean spectrum using a single Gaussian. We then kept the width and the shift in the individual-night spectra, but left the line intensity as a free parameter.

The intensity variation of the He II lines in our sample will be discussed in a forthcoming publication. Here we only note that the procedure described above seems to be consistent with the observations, and in general, the lag of this line is much shorter than the Hβ lag.

3.1.6. Host Galaxy

Following Barth et al. (2013), we use single simple stellar population models from Bruzual & Charlot (2003) as templates for the galaxy component. For most objects in our sample, the instantaneous-burst model with an age of 11 Gyr and solar metallicity (Z = 0.02) provided a sufficiently good fit to the mean spectrum and a consistent flux ratio compared with the measured Hubble Space Telescope (HST) images (see Papers I and II). In a few cases (Mrk 335, Mrk 142, and Mrk 42), this template gives a flux that is much larger than that derived from the HST image. The template with 11 Gyr and Z = 0.05 provides better results and was adopted in these cases.

Like the Fe II template, the galaxy template is also convolved with a Gaussian to be scaled, broadened, and shifted. As described previously and detailed in Appendix A, the relative flux \( F_{\text{gal}} \) is free to vary in the fitting of individual-night spectra.

3.2. Fitting Results

Table 1 lists the values of the parameters fixed in the fitting of individual-night spectra for all the objects in our sample. Columns (5)–(12) list the narrow emission lines included in the fits. As explained, their velocity widths and shifts are constrained to be the same as those of the \([\text{O} \text{iii}]\) λ5007 line, while the relative intensity ratios are kept as measured from the mean spectrum. The last column gives the galaxy template used. In the table, a blank entry means that a spectral component is not included for the object.

Figure 3 shows examples of fittings to individual-night spectra for the eight objects not presented so far. The notations and colors are as the same as those in Figure 1 for Mrk 382. Notes on two objects with unusual treatments are as follows.

IRAS 04416+1215. This object has the highest redshift (0.089) in our sample. From the images taken for slit centering, the point-spread function of the object is as broad as that of the comparison star, meaning that there is a negligible galaxy contribution. For this object, the comparison star is fainter than the AGN, especially in the red part. We found that the shape of the spectrum of this object is not as well calibrated by the comparison star as in the other objects. Thus, we fit in a relatively narrow wavelength window (4430–5550 Å), but covering the two bumps of Fe II emission on either side of Hβ. We also let the spectral index, \( \alpha \), of the AGN power-law continuum free to vary in individual-night spectra to compensate for the difference in spectral shape caused by the calibration. As shown in Figure 3, the spectrum can be fitted well by including only a power law, Fe II emission, Hβ, [O iii], and a few narrow lines.

IRAS F12397+3333. As discussed in Paper I, the spectrum of this AGN is probably affected by host galaxy extinction. The observed spectra (see Figure 4 of Paper I for an example) have a very red color, and are badly fitted by our spectral model. We perform an extinction correction after de-redshifting, assuming the Galactic extinction law and \( A_V = 1.44 \) mag estimated from the Balmer decrement (see details in Paper I). This dereddened spectrum is fit well with a typical spectral index, as shown in Figure 3.

3.3. Line-profile Measurements

For each individual-night spectrum, the fluxes, FWHMs, and velocity shifts (with respect to [O iii]) of Fe II and Hβ are calculated from the best-fit model. The means of these properties are considered to be the measurements of the line profile, except for the width of Hβ (FWHM_{H\beta}; see below). The standard deviations on those means are used as the uncertainties.

FWHM_{H\beta} is underestimated in the fitting, as we do not include the narrow component of Hβ in our model (see Section 3.1.3). Thus, we use a different method to estimate this width. We add a Gaussian to our model to represent the narrow Hβ component. The velocity width and shift are constrained to be the same as those of [O iii]. We then fit the mean spectra twice, once assuming the flux of the narrow Hβ line is 10% of the flux of [O iii] λ5007 and once assuming a flux ratio of 0.2. The width of the broad Hβ obtained with a flux ratio set to 0.1 is adopted as the FWHM_{H\beta}. The uncertainty is obtained from the fit with a flux ratio set to 0.2 and the original fit that assumed no narrow Hβ. This method essentially resembles the one used in Papers I and II, while the spectral model here is more sophisticated.

Table 2 lists the measurements of the 10 objects. The instrumental broadening (FWHM ∼500 km s\(^{-1}\), Section 3.1.3) has been taken into account in the listed FWHMs. Note that the Hβ of IRAS 04416+1215 has a large velocity-shift with
### Parameters Fixed in the Fitting of Individual-night Spectra

| Object       | Power Law | Broad He \( \lambda 4686 \) | Narrow Emission Lines | Galaxy Model |
|--------------|-----------|-------------------------------|-----------------------|--------------|
|              | \( \alpha \) | FWHM \( (\beta \propto \lambda^n) \) | Shift \( (\text{km s}^{-1}) \) | \( \text{He} \alpha \) | \( \text{He} \beta \) | \( \text{Fe} \text{vi} \) | \( \text{Fe} \text{vii} \) | \( \text{Fe} \text{vii} \) | \( \text{N} \text{vi} \) | \( \text{Ca} \text{v} \) | \( \text{Fe} \text{vi} \) | \( \text{Fe} \text{vii} \) |                     |
|---------------|------------|-------------------------------|-----------------------|--------------|
| Mrk 335       | −1.45      | −620                          | 0.042                 | 0.115        | 0.043        | 0.032       | ...         | 0.028        | 0.057        | 0.079       | 11 Gyr z05    |                     |
| Mrk 1044      | −2.01      | −942                          | 0.216                 | ...          | 0.117        | 0.219       | ...         | ...          | 0.205        | 0.225       | 11 Gyr z02    |                     |
| IRAS 04416+1215 | free\(^a\) | ...                          | ...                   | ...          | ...          | ...         | ...         | ...          | ...          | ...         | ...          |                     |
| Mrk 382       | −1.96      | −1322                         | 0.028                 | 0.074        | ...          | ...         | ...         | ...          | 0.021        | 0.033        | 0.021       | 11 Gyr z05    |                     |
| Mrk 142       | −2.11      | −757                          | 0.041                 | 0.131        | 0.055        | 0.116       | ...         | ...          | 0.082        | 0.095       | 11 Gyr z05    |                     |
| MCG +06−26−012 | −0.84      | −927                          | 0.063                 | 0.096        | ...          | ...         | ...         | ...          | 0.046        | 0.061       | 11 Gyr z02    |                     |
| IRAS F12397+3333\(^c\) | −2.28      | −334                          | ...                   | 0.034        | 0.013        | ...         | 0.018       | ...          | 0.008        | 0.010       | 11 Gyr z02    |                     |
| Mrk 42        | −0.76      | −55                           | 0.069                 | 0.093        | ...          | ...         | ...         | ...          | ...          | ...         | ...          |                     |
| Mkr 486       | −0.76      | −724                          | 0.171                 | 0.027        | ...          | ...         | 0.067       | 0.050        | 0.140       | 11 Gyr z02    |                     |
| Mkr 493       | −0.91      | −1580                         | 0.132                 | 0.261        | ...          | ...         | ...         | ...          | ...          | ...         | ...          |                     |

**Notes.** Fixed parameters in the fitting of individual-night spectra. Columns (2)–(4) list the absolute values of the parameters. Columns (5)–(12) list the relative intensity ratios with respect to \([\text{O} \text{iii}] \lambda 5007\) for the narrow emission lines. Column (13) lists the galaxy template from Bruzual & Charlot (2003). \(\cdots\) means that the component is not included in the fitting for the specific object.

\(^a\) The FWHMs listed are after instrumental broadening correction.

\(^b\) The spectral index of the power-law continuum is free to vary in the fitting of the IRAS F04416+1215 spectra. See the text for details.

\(^c\) Intrinsic host galaxy extinction is assumed in the fitting of IRAS F12397+3333. See the text for details.

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With respect to \([\text{O} \text{iii}] \lambda 5007\), and its profile features no narrow component with the same shift of \([\text{O} \text{iii}]\). Adding a narrow component makes the width of the broad \(H\beta\) even narrower. Thus, the FWHM of IRAS 04416+1215, as with other properties, was obtained from the measurements of individual-night spectra.

### 3.4. Light Curve Measurements

Our fitting successfully reduces the scatter in the light curves due to the influence of the host galaxy contamination; thus, \(F_{\text{AGN}}\) represents the real AGN continuum much better than the simply integrated 5100 Å flux \(F_{5100}\), as shown in Appendix A. The light curves of the emission lines are also generated directly from the best-fit values of the corresponding parameters that were obtained from the fits of individual-night spectra. The errors of the fluxes given by the fitting are not large enough to account for the scatter in the fluxes of successive nights; an additional systematic error is estimated for each light curve (as in Paper I). This systematic error is added in quadrature to the fitting error for the calculations of variability amplitudes and time lags below. Note that our treatment is different from that of Barth et al. (2013), who measured the light curve of \(H\beta\) by integrating the continuum-subtracted spectra.

### 4. LIGHT CURVE ANALYSIS AND RESULTS

Figure 4 (left column) and Figure 5 show the light curves of \(F_{\text{AGN}}, F_{\text{H} \beta}\) and \(F_{\text{Fe}}\) for nine objects with reliable lag measurements, and the remaining one (Mkr 42), respectively. In this section, we will calculate the variability amplitudes and the reverberation lags for the \(H\beta\) and \(Fe\) emission lines. We then compare the \(H\beta\) time lags with those that were presented in Papers I and II.

#### 4.1. Variability Amplitudes

We use the quantity \(F_{\text{var}}\) defined in Rodríguez-Pascual et al. (1997) to represent the variability amplitude. This quantity is an estimate of the intrinsic variability over the errors. The uncertainties are calculated following Edelson et al. (2002). The results for \(Fe\) and \(H\beta\) are listed in Table 3. For the variability amplitude ratio of \(Fe\) to \(H\beta\), the range is about 0.6 (Mkr 486) to 1.2 (Mkr 42), except for Mkr 382, which has the largest host galaxy contamination. On average (except for Mkr 382), the \(Fe\) value is about 10% smaller, consistent with previous results (e.g., Vestergaard & Peterson 2005; Barth et al. 2013).

#### 4.2. Reverberation Lags

The time lags between the AGN continuum variations \(F_{\text{AGN}}\) and the emission lines \(F_{\text{Fe}}\) and \(F_{\text{HI}}\) are measured from the cross-correlation functions (CCFs) of the relevant light curves. We use the interpolation cross-correlation function (Gaskell & Sparke 1986; Gaskell & Peterson 1987; White & Peterson 1994) method to calculate the CCF, and adopt the centroid of the CCF, above 80% of the peak value \(r_{\text{max}}\) as the time lag (Koratkar & Gaskell 1991; Peterson et al. 2004). The uncertainty in the time lag measurement is estimated from the cross-correlation centroid distribution (CCCD) given by random subset selection/flux randomization Monte Carlo realizations (Maoz & Netzer 1989; Peterson et al. 1998).

All of the objects in our sample, except for Mkr 42, have reliable time lag measurements for both \(Fe\) and \(H\beta\). The right columns of Figure 4 show the results of the CCF analysis. For each object, the top right panel shows the autocorrelation function of the \(F_{\text{AGN}}\) light curve, which is shown in the top left panel. The two lower panels in the right column show the CCFs (in black) for \(H\beta\) (middle right) and \(Fe\) (bottom right), with respect to \(F_{\text{AGN}}\) light curves. The blue histograms are the corresponding CCCDs. Most CCCDs
have a rather symmetric profile, except those for IRAS 04416+1215.

Table 4 lists the time lags of FeII ($\tau_{Fe}$) and Hβ ($\tau_{H\beta}$), their uncertainties, and the corresponding $r_{max}$ for the nine objects with reliable lag measurements. The listed time lags and uncertainties are in the rest frame after time-dilation correction. Both of the time lags for IRAS 04416+1215 have uncertainties of highly unequal upper and lower limits as the sequence of their asymmetric CCCDs. For other objects, the time lags are well determined by the single-peak CCFs with high $r_{max}$ and symmetric, narrow CCCDs.

The detection rate of the FeII time lag in our sample is extremely high (9 in 10) compared with previous RM experiments. This is mainly attributed to the common feature of strong Fe II emission in the SEAMBH sample, the high-cadence observation, and sophisticated spectral fitting. The failure to obtain reliable $\tau_{Fe}$ and $\tau_{H\beta}$ in Mrk 42 is caused by the $F_{AGN}$ light curve, which has large scatter and no clear structure (see Figure 5). However, the light curves of $F_{Fe}$ and $F_{H\beta}$ show hints of a similar structure, which, unfortunately, is not enough to establish a time lag.

The clear reverberation of the Fe II emission in response to the continuum supports the hypothesis that the Fe II emission originates from photoionized gas in the BLR. The high detection rate indicates that this is prevalent in NLS1, which are AGNs with high $L_{bol}/L_{Edd}$. It is possible that the origin of Fe II emission in AGNs with low $L_{bol}/L_{Edd}$ is different, but there is little evidence to support this claim. In fact, Barth et al.
(2013) already detected the reverberation of Fe II in two broad-line Seyfert 1 galaxies with Hβ widths of FWHM $\gtrsim$ 4000 km s$^{-1}$ and much lower $L_{bol}/L_{Edd}$. Comparing the time lags of FeII and Hβ, along with their velocity widths, provides some hints about the location and geometries of the two emission regions. We will discuss these ideas in Section 5.2 below.

### 4.3. Hβ Lag Comparison

In Paper I and Paper II, the reported time lags of Hβ are obtained from the light curves that were measured by the more traditional integration method, without taking into account the contamination by the host galaxy and the narrow emission lines. Figure 6 shows a comparison between the previously reported $\tau_{H\beta}$ that is based on the integration method and the new results given by the fitting method reported here. The dashed diagonal line denotes the 1:1 ratio and the region between the two dotted lines gives the 0.1 dex deviation from the line. For seven out of nine objects, the differences between $\tau_{H\beta}$ given by the two methods are less than 0.1 dex. The two exceptions are IRAS 04416+1215 and Mrk 1044. In Paper II we show that using the integration method, we cannot obtain a significant $\tau_{H\beta}$ for IRAS 04416+1215. The lag for Mrk 1044 that is reported in that paper is about a factor of 2 shorter than...
Table 2
Line-profile Measurements

| Object | Flux (10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}) | FWHM (\text{ km s}^{-1}) | Shift (\text{ km s}^{-1}) | Flux (10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}) | FWHM (\text{ km s}^{-1}) | Shift (\text{ km s}^{-1}) |
|--------|-----------------------------------------------|--------------------------|--------------------------|-----------------------------------------------|--------------------------|--------------------------|
| Mrk 335 | 253 ± 9                                        | 1947 ± 143               | 49 ± 37                  | 661 ± 22                                        | 2096 ± 170               | −1 ± 16                  |
| Mrk 1044 | 369 ± 11                                      | 866 ± 25                 | 76 ± 10                  | 380 ± 16                                        | 1178 ± 22                | 12 ± 12                  |
| IRAS 04416+1215 | 292 ± 9                                    | 1313 ± 50                 | 496 ± 21                 | 149 ± 4                                        | 1522 ± 44*               | 241 ± 29                 |
| Mrk 382 | 27 ± 4                                        | 1326 ± 234               | 13 ± 115                 | 39 ± 2                                         | 1462 ± 296              | −44 ± 35                 |
| Mrk 486 | 87 ± 5                                        | 1512 ± 69                | −25 ± 37                 | 78 ± 5                                         | 1588 ± 58               | −101 ± 28                |
| Mrk 42 | 41 ± 4                                        | 1155 ± 70                | −21 ± 41                 | 41 ± 4                                         | 1334 ± 80               | −29 ± 23                 |
| Mrk 382 | 550 ± 28                                      | 1748 ± 78                | 36 ± 40                  | 405 ± 18                                       | 1802 ± 560              | −50 ± 26                 |
| Mrk 42 | 67 ± 3                                        | 787 ± 16                 | 105 ± 19                 | 57 ± 2                                         | 802 ± 18                | 87 ± 19                  |
| Mrk 486 | 186 ± 5                                       | 1790 ± 88                | 95 ± 33                  | 346 ± 12                                       | 1942 ± 67               | −46 ± 9                  |
| Mrk 493 | 102 ± 3                                       | 780 ± 9                  | 171 ± 9                  | 92 ± 3                                         | 778 ± 12                | 126 ± 13                 |

Notes. Fluxes, FWHMs, and velocity shifts of Fe\(\text{II}\) and H\(\beta\). Except for the H\(\beta\) FWHMs, the listed values are the means and standard deviations obtained from the measurements of individual-night spectra. All listed FWHMs include a correction due to instrumental broadening. The velocity-shifts are with respect to [O\text{III}].

\(\text{H}\beta\) FWHMs are estimated from the mean spectrum of each object, taking into account the narrow H\(\beta\) component, as explained in the text.

\(\text{H}\beta\) FWHM for IRAS 04416+1215 is obtained from individual-night spectra. See the text for details.

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obtained here, with a very large uncertainty \(4.8^{+3.2}_{-5.3}\). This value is consistent with the new one presented here within the uncertainties. In addition, the uncertainty of \(\tau_{\text{H}\beta}\) in Mrk 493 given by the integration method is very large, with a negative lower limit \(12.2^{+3.5}_{-16.2}\). The fitting method yields a much smaller uncertainty with basically the same \(\tau_{\text{H}\beta}\). This is a direct result of the much smoother H\(\beta\) light curve of Mrk 493 given by the fitting method (see Figure 4, and also Figure 2 of Paper II). Thus, the time lags of H\(\beta\) given by the two methods are consistent with each other and \(\tau_{\text{H}\beta}\) is better defined by the fitting procedure in some of the cases.

5. DISCUSSION

5.1. The Radius–Luminosity Relationship for Fe\(\text{II}\)

A simple theoretical expectation based on photoionization is that \(R_{\text{BLR}} \propto L^{\alpha}\) with \(\alpha \sim 0.5\). The \(R_{\text{BLR}}-L\) relation for H\(\beta\) has been compared with such predictions in several earlier publications (e.g., Kaspi et al. 2000; Bentz et al. 2009, 2013, and references therein). Regarding Fe\(\text{II}\) lines, Chelouche et al. (2014) provide a tentative \(R_{\text{BLR}}-L\) relation for the first time, from a small inhomogenous sample of six AGNs. Among them, two objects are reported by Barth et al. (2013) using the standard spectral fitting method, and four others come from Rafter et al. (2013) and Chelouche et al. (2014), using the MCF scheme of Chelouche & Zucker (2013). Here, we revisit this issue by more than doubling the size of the sample by adding our nine newly measured sources. For a proper comparison with the Chelouche et al. (2014) results, we used our best observed fluxes and uncertainty, and a cosmology with \(H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}\), \(\Omega_m = 0.3\), and \(\Omega_{\Lambda} = 0.7\).

Figure 7 shows \(\tau_{\text{Fe}}\) versus the 5100 Å luminosity for the nine objects in our sample (black dots) alongside the earlier results (kindly provided by D. Chelouche). The green squares are those obtained by the MCF scheme (including three with insignificant results; see Figure 4 of Chelouche et al. 2014 for details). The blue triangles are the two objects from Barth et al. (2013) for which we used the centroid of the published CCFs for Fe\(\text{II}\) and the V-band light curves. Using the FITEXY method (Press et al. 1992) to fit all the 18 objects, we find

\[
\log(R_{\text{Fe}\text{II}\text{BLR}}) = (-22.0 \pm 1.1) + (0.54 \pm 0.02)\log(L_{\lambda}(5100\text{Å})),
\]

which is plotted as a solid line. This line deviates considerably from the relation presented in Chelouche et al. (2014), shown as a dotted line, but is close to that of Bentz et al. (2009) for H\(\beta\) (dashed line). This result is expected since most of the objects in our sample show roughly equal \(\tau_{\text{Fe}}\) and \(\tau_{\text{H}\beta}\) (see Table 4), except for three objects (Mrk 335, Mrk 382, and Mrk 486), while the previous studies have \(\tau_{\text{Fe}}\) greater than \(\tau_{\text{H}\beta}\). Our sample by itself shows no correlation at all between \(\tau_{\text{Fe}}\) and the 5100 Å luminosity. This is not surprising given the relatively small range of luminosity we have considered here, and the fact that for this sample, the correlation between \(\tau_{\text{H}\beta}\) and the continuum luminosity is also very weak. We suggest that this lack of correlation is also related to the large \(L_{\lambda 5000}/L_{\text{edd}}\) of the objects in our sample, a topic we discuss in great detail in Paper IV (Du et al. 2015).

5.2. Comparison between Fe\(\text{II}\) and H\(\beta\)

As shown in Table 4 \(\tau_{\text{Fe}}\) is roughly equal to \(\tau_{\text{H}\beta}\) (counting the uncertainties in both lags) in six of our objects, longer in two (Mrk 335 and Mrk 382), and somewhat shorter in one (Mrk 486). A common feature of the three objects with unequal lags is the relatively low Fe\(\text{II}/H\beta\) intensity ratio. Figure 8 shows the plot of \(\tau_{\text{Fe}}/\tau_{\text{H}\beta}\) versus \(F_{\text{Fe}}/F_{\text{H}\beta}\) (defined as \(R_{\text{Fe}}\)). The three objects with different time lags are labeled by their names and located in the region of \(R_{\text{Fe}} < 1\). The six other objects show \(R_{\text{Fe}} > 1\). We also mark the approximate positions of the two objects that were measured by Barth et al. (2013).\(^{10}\) Based on eye estimates of the published light curves shown in their paper, both objects have \(R_{\text{Fe}} \sim 0.75\). Their positions in Figure 8 are marked around 0.75 (and horizontally shifted for clarity).

\(^{10}\) The Fe\(\text{II}\) flux in Barth et al. (2013) is defined as the integrated flux of Fe\(\text{II}\) between 4400 and 4900 Å, while our definition refers to the range between 4434 and 4684 Å. For the Fe\(\text{II}\) template of Boreson & Green (1992), \(F_{\text{Fe}}\) defined here is about 3/4 that in Barth et al. (2013).
They both have different time lags than Hβ and RFe < 1, consistent with the results of our sample. We note, again, that our sample is highly biased toward AGNs with high Lbol/Ledd and thus high RFe. In an unbiased AGN sample, the fraction of sources with RFe < 1 is much larger (see, e.g., Figure 7 of Sulentic et al. 2000 and Figure 1 of Shen & Ho 2014). Hu et al. (2008) analyzed the properties of a large number of low-redshift AGNs. They found that the velocity width of FeII is systematically narrower (∼3/4) than that of Hβ, which may suggest, given Keplerian velocities, that in those sources τFe is longer than τHβ. Our present sample contains only 10 sources, which is too few to systematically test any of these ideas.

6. SUMMARY

We provide new Fe II measurements for 10 NLS1s and report statistically significant time lag measurements for nine of these sources. All of the observed NLS1s are suspected to be SEAMBHs. This more than doubles the number of AGNs showing measurable Fe II time lags. Our time lag measurements are based on high-cadence, high signal-to-noise measurements at the Yunnan observatory, and a new, sophisticated fitting analysis that takes into account the uncertainties caused by the apparent flux change of the host galaxy and several narrow emission lines. We demonstrate, by a careful comparison with earlier measurements of τHβ, that the method can considerably improve the accuracy of the time lag measurement. The main findings reported in this paper can be summarized as follows.

1. All 10 objects presented here show Fe II variations with an amplitude of a few to ten percent. On average, this is about 10% smaller than the variability of the Hβ line.
2. Reliable Fe II reverberation time lags with respect to the AGN continuum are detected in nine objects, confirming the suggestion that the Fe II emission originates from photoionized gas.
Figure 4. (Continued.)
The listed values are in percentage.

Note. Mrk 493 also has very large intrinsic scatter over a small luminosity range.

Object

Fe II

Hβ

Mrk 335

0.48

3.1 ± 0.3

3.0 ± 0.3

Mrk 1044

2.6 ± 0.3

3.7 ± 0.4

IRAS 04416+1215

2.1 ± 0.3

2.0 ± 0.3

Mrk 382

11.5 ± 1.2

4.1 ± 0.4

Mrk 142

5.5 ± 0.5

6.6 ± 0.5

MCG +06–26–012

8.1 ± 1.2

9.2 ± 1.2

IRAS F12397+3333

4.4 ± 0.6

4.1 ± 0.5

Mrk 42

3.6 ± 0.7

2.9 ± 0.4

Mrk 486

2.0 ± 0.5

3.4 ± 0.4

Mrk 493

2.1 ± 0.7

3.1 ± 0.5

Note. The listed values are in percentage.

3. Combining the new RM results with those in previous work shows a clear radius–luminosity relationship for Fe II that is similar to that for Hβ. However, our sample by itself shows no such correlation, due to the large intrinsic scatter over a small luminosity range.

4. The difference in the time lags of Fe II and Hβ depends on the intensity ratio of Fe II to Hβ (RFe). The time lag of Fe II is roughly equal to that of Hβ in all the six objects with RFe ≥ 1. The Fe II time lag is longer in Mrk 335 and Mrk 382, which have RFe < 1, and shorter in Mrk 486 with RFe < 1.

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APPENDIX A

HOST GALAXY FLUX CALIBRATION

Our flux calibration method provides the relative flux of the object with respect to that of the local comparison star. For two point sources kept in a line parallel to the slit, the fractions of

Figure 5. Light curves of the AGN (top panel), Hβ (middle), and Fe II (bottom) for Mrk 42. Note the similarity of the light curves of Hβ and Fe II.

Figure 6. Comparison of the Hβ time lags obtained by simple integration (Papers I and II) with those obtained by fitting (this work). The differences are typically less than 0.1 dex (dotted lines) except for IRAS 04416+1215 (not plotted because its τHβ cannot be defined by integration) and Mrk 1044 (very large uncertainty of the integration method). Mrk 493 also has very large uncertainty when measured by the integration method, but the measured τHβ are very similar.
light loss due to seeing, differential atmospheric refraction, and mis-centering are identical. Thus this method gives an accurate relative flux calibration for the spectral components of the AGN, including the featureless power law ($F_{\text{AGN}}$) and the broad emission lines. This is not the case for the extended host galaxies whose flux relative to the comparison star inside the slit can vary much more due to seeing variations and mis-centering. In addition, different parts of the galaxy may be observed each time. As a result, the derived flux of the host galaxy is $F_{\text{gal}} = f_{\text{cal}} F_{\text{gal,abs}}$, where $F_{\text{gal,abs}}$ is the absolute flux (which is constant), and $f_{\text{cal}}$ is a factor accounting for all the effects of varying observing conditions in the flux calibration procedure. $f_{\text{cal}}$ could change from one exposure to the next, introducing an additional uncertainty into the integrated 5100 Å flux $F_{5100} = F_{\text{AGN}} + f_{\text{cal}} F_{\text{gal,abs}}$.

In Papers I and II, we estimated the flux of the host galaxies in the spectral extraction aperture using archival HST images for eight objects in our sample. The resultant relative fluxes,
(F_{gal}/F_{AGN}), range from ~0.2 in Mrk 335 to ~1 in Mrk 382. Thus, the apparent change in flux of the host galaxy is not negligible for those objects with strong host galaxy contribution. For Mrk 382, the measurement of the AGN continuum was badly affected by this uncertainty, which forced us to use the V-band photometry instead. The new procedure adopted here (see the main text) enables us to solve for $f_{\text{gal}} F_{\text{gal,abs}}$ for each individual-night spectrum. The detailed fitting of the various spectral components considerably reduces the noise in the various line and continuum light curves. In particular, for Mrk 382, we can now recover the 5100 Å AGN continuum variations to a much better accuracy, which is evident by the good agreement with the V-band photometry.

The big improvements due to the spectral fitting procedure are shown in Figure 9, which provides more information on the process for Mrk 382. The top panel shows the light curve of

**Figure 10.** Light curves of Fe ii measured by simple integration ($F_{\text{Fe,intg}}$). All have a larger scatter compared with those obtained by fitting shown in Figures 4 and 5.
Fe II LIGHT CURVES MEASURED BY INTEGRATION

We present the Fe II light curves measured by the traditional integration method for a comparison with that by the present fitting scheme in this appendix. The flux of the Fe II bump on the red side of [O III] λ5007 is calculated by integrating in 5115–5465 Å the flux above the straight line set by two continuum windows 5085–5115 and 5465–5495 Å (the three bands are in the rest frame). Figure 10 shows these light curves. Compared with those given by the fitting method (in Figures 4 and 5), all the light curves by integration show a larger scatter. For four objects (Mrk 1044, Mrk 142, MCG +06–26–012, and IRAS F12397+3333), rough structures can be recognized in their light curves, and the derived Fe II time lags are consistent with those given by the fitting, but with larger uncertainties. The remaining objects fail to have reliable measurements of time lag for their scattered light curves without clear structures. We also tried to measure the flux of the Fe II bump on the blue side of H β by choosing an integration interval avoiding the broad He II line. Similarly, light curves with poor quality are obtained.

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