SUPERMASSIVE BLACK HOLES WITH HIGH ACCRETION RATES IN ACTIVE GALACTIC NUCLEI. VI. VELOCITY-RESOLVED REVERBERATION MAPPING OF THE H$\beta$ LINE

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ABSTRACT

In the sixth of a series of papers reporting on a large reverberation mapping (RM) campaign of active galactic nuclei (AGNs) with high accretion rates, we present velocity-resolved time lags of H$\beta$ emission lines for nine objects observed in the campaign during 2012–2013. In order to correct the line broadening caused by seeing and instruments before analyzing the velocity-resolved RM, we adopt the Richardson–Lucy deconvolution to reconstruct their H$\beta$ profiles. The validity and effectiveness of the deconvolution are checked using Monte Carlo simulation. Five among the nine objects show clear dependence of the time delay on velocity. Mrk 335 and Mrk 486 show signatures of gas inflow whereas the clouds in the broad-line regions (BLRs) of Mrk 142 and MCG +06-26-012 tend to be radial outflowing. Mrk 1044 is consistent with having virialized motions. The lags of the remaining four are not velocity-resolvable. The velocity-resolved RM of super-Eddington accreting massive black holes (SEAMBHs) shows that they have diverse kinematics in their BLRs. Comparing with the AGNs with sub-Eddington accretion rates, we do not find significant differences in the BLR kinematics of SEAMBHs.

Key words: accretion, accretion disks – galaxies: active – quasars: supermassive black holes

1. INTRODUCTION

Active galactic nuclei (AGNs) are very energetic sources powered by accretion onto supermassive black holes (SMBHs) in centers of their host galaxies. In optical/ultraviolet (UV) spectra of AGNs, the most prominent features are plenty of broad emission lines whose FWHM spans from $\sim$10$^3$ to $2 \times 10^4$ km s$^{-1}$ (e.g., Schmidt 1963; Osterbrock & Mathews 1986; Boroson & Green 1992; Sulentic et al. 2000; Shen et al. 2011, and references therein). These emission lines originate from the gas in the broad-line regions (BLRs), which is photoionized by the continuum from central engines (Osterbrock 1989; Ho 2008). In the past decades, reverberation mapping (RM, e.g., Bahcall et al. 1972; Blandford & McKee 1982; Peterson et al. 1993) has become the mainstay in the study of the kinematics and geometry of BLRs, as well as in measuring the masses of SMBHs in the centers of AGNs. It discerns the BLRs in the time domain, instead of the spatial domain, by spectroscopically monitoring the response of broad emission lines to the variations of continuum fluxes. RM observation has been carried out for more than 50 AGNs by many different groups (Peterson et al. 1993, 1998, 2002, 2004; Kaspi et al. 2000, 2007; Bentz et al. 2008, 2009b; Denney et al. 2009a; Barth et al. 2011, 2013, 2015; Rafter et al. 2011, 2013; Du et al. 2014, 2015; Wang et al. 2014; Shen et al. 2015), and has successfully measured their time delays between the variations of continuum and emission lines. Enormous progress has been made in understanding the BLRs through RM observations (see recent reviews, e.g., Gaskell 2009; Popović 2012; Netzer 2013).

However, a main objective of RM is to reconstruct the so-called velocity-delay map (also known as “transfer function”), which is a function of the time lag and line of sight velocity of BLR gas, instead of only getting an averaged time lag of the emission line (Blandford & McKee 1982; Horne 1994; Horne et al. 2004). Due to the requirements of homogeneous sampling, accurate calibration, excellent signal-to-noise ratios (S/Ns), and high resolution for the reconstruction of velocity-delay maps (Horne et al. 2004), a relatively simpler analysis, which measures the time lags of emission lines as a function of line of sight velocity (velocity-resolved time lags), has been applied to about a dozen AGNs (e.g., Bentz et al. 2008, 2009b, 2010; Denney et al. 2009a, 2010; Grier et al. 2013). This analysis reveals the kinematics and geometry of their BLRs. It is very similar to the projection of the velocity-delay map on the velocity axis. Furthermore, some more recent works have recovered the velocity-delay maps in several AGNs successfully by using maximum entropy methods (Bentz et al. 2010; Grier et al. 2013) or the Markov Chain Monte Carlo method (Pancoast et al. 2011, 2012, 2014a, 2014b; Li et al. 2013).

Since 2012, we have started a large RM campaign to monitor a sample of AGNs with high accretion rates, especially super-Eddington accreting massive black holes (SEAMBHs). The goal of the campaign is to understand better super-Eddington accretion onto black holes, the BLR physics, and their potential as a new probe of cosmological distance (Wang et al. 2013, 2014). The observations and light curves of H$\beta$ emission line in the first year (2012–2013) have been published.
Table 1
Stellar Template

| Object  | Stellar Template | Spectral Type |
|---------|------------------|---------------|
| Mrk 335 | HD 77818         | K1 IV         |
| Mrk 1044 | HD 173399       | G5 IV         |
| IRAS 04416 + 1215 | HD 10307 | G1.5 V        |
| Mrk 382 | SAO 126242       | F7 IV         |
| Mrk 142 | HD 142373        | F8 Ve         |
| MCG +06-26-012 | HD 131156 | G8 V          |
| IRAS F12397 + 3333 | HD 118100 | K5 Ve         |
| Mrk 486 | HD 20618         | G6 IV         |
| Mrk 493 | HD 118100        | K5 Ve         |

Notes. Name and spectral type of the selected template for the comparison stars.

* The spectra type listed in Valdes et al. (2004).

2. OBSERVATIONS AND DATA REDUCTION

Details of the target selection, instruments, observation, and procedures of the data reduction of the campaign in 2012–2013 (hereafter SEAMBHB2012) have been presented by Papers I and II. For completeness, in this section, we provide a brief summary of the main points.

2.1. Sample Selection

The targets selected for SEAMBHB2012 are mainly narrow-line Seyfert 1 galaxies (NLS1s; see, e.g., Osterbrock & Pogge 1985), which, as a peculiar group of AGNs, are suspected to be candidates of SEAMBHs. The characteristics of NLS1s are (1) narrow Balmer lines (FWHM \(\lesssim 2000\) km s\(^{-1}\)), (2) strong optical Fe \(\text{II}\) emission (relative to H\(\beta\)), (3) weak [O \text{II}] lines, and (4) steep hard X-ray spectrum (Osterbrock & Pogge 1985; Boller et al. 1996). We selected NLS1s with an extremely steep 2–10 keV continuum, which is known to anticorrelate with accretion rates (Wang et al. 2004). For the SEAMBHB2012 sample, we monitored nine NLS1s successfully, the names and coordinates of which are summarized in Table 1 of Paper II.

2.2. Spectroscopy and Data Reduction

All of the spectroscopic observations were carried out with the Yunnan Faint Object Spectrograph and Camera which is mounted on the Lijiang 2.4 m telescope at the Yunnan Observatories of the Chinese Academy of Sciences. To obtain spectra with highly accurate flux calibration, we oriented the long slit to take the spectra of the object and a nearby non-varying comparison star (used as standard) simultaneously. This method was applied early in the RM campaign in Maoz et al. (1990) and Kaspi et al. (2000). In SEAMBHB2012, we fixed the slit width to 2.5 given the seeing conditions, and used Grism 14 with a resolution of 92 \(\AA\) mm\(^{-1}\) and a wavelength coverage of 3800–7200 \(\AA\), which yields a final \(\sim 1.8\) \(\AA\) pixel\(^{-1}\) \((\sim 108\) km s\(^{-1}\) pixel\(^{-1}\)) in dispersion direction. All of the spectroscopic data were reduced with IRAF v2.16 and the flux was calibrated by comparing spectra of the targets with those of the comparison stars in the slit. Readers are referred to Paper I for more details.

3. CORRECTION FOR LINE BROADENING

In spectroscopic observation, the line broadening (\(\xi\)), which is caused by the seeing and instruments (e.g., grism or grating), influences the observed profiles of emission lines. Although the instrumental settings remain the same during observations, the seeing varies night by night (the FWHM of the point-spread functions in SEAMBHB2012 is generally from 1.2 to 2.5), while the width of the slit is fixed to 2.5, which is wider than the seeing), and \(\xi\) in each night changes as well. Furthermore, the mismatching of objects and comparison stars in the slit is not a constant on different nights. This causes each spectrum to have a slightly different shift in dispersion direction. Fortunately, we are also able to estimate the shifts from the spectra of comparison stars so that we can correct this automatically by deconvolution.

The observed H\(\beta\) profile of \(I_{obs}\) is a convolution of its intrinsic profile \(I_{int}\) and the line-broadening function \(\xi\), namely

\[
I_{obs}(\lambda) = I_{int}(\lambda) \otimes \xi(\lambda) = \int I_{int}(\chi) \xi(\lambda - \chi) d\chi. \tag{1}
\]

Variations of \(\xi\) do not change the integrated flux of the H\(\beta\) emission line; however, it blurs \(I_{int}\) and further influences the velocity-resolved time-series analysis. It is thus expected to correct the line broadening of H\(\beta\) profiles before the velocity-resolved RM analysis, especially for those objects with relatively narrow H\(\beta\) lines (FWHM \(\sim 1000–2000\) km s\(^{-1}\), compared to the instrumental broadening of \(\sim 500\) km s\(^{-1}\) estimated in Paper I) in our SEAMBHB2012 observation. Fortunately, the spectra of comparison stars in the same slit during spectroscopic exposures can be employed to estimate \(\xi\) accurately in light of the fact that the FWHM of absorption lines in stellar spectra (\(\lesssim 10\) km s\(^{-1}\)) is much narrower than the line broadening. An efficient way to perform such a correction is the well-known Richardson–Lucy (R–L) algorithm (Richardson 1972; Lucy 1974) which can deconvolve \(\xi\) from \(I_{obs}\) so as to recover \(I_{int}\).

Figure 1 shows the flowchart of the procedures for line-broadening correction. We first estimate the broadening function \(\xi\) of the exposure by fitting the spectrum of the comparison star in each night by a stellar template. We then use the obtained \(\xi\) to correct the broadening of the H\(\beta\) profile \(I_{obs}\) in...
the observed spectra through the R–L deconvolution algorithm. Finally, we can get the broadening-corrected profile \( I_{\text{int}} \).

### 3.1. R–L Deconvolution

The R–L deconvolution algorithm is a Bayesian-based iterative technique commonly used for recovering signal blurred by a known response. It has been widely adopted to improve the spatial resolution of images from the Hubble Space Telescope (HST), e.g., Lauer et al. 1993, 1995, 2005; Snyder et al. 1993; Gebhardt et al. 1996; Schmitt & Kinney 1996; Kormendy & Bender 1999; Farrah et al. 2001; Rest et al. 2001, and the references therein) and to correct the instrumental broadening in spectroscopic data such as UV spectra from Goddard High Resolution Spectrograph on HST (e.g., Wahlgren et al. 1991; Brandt et al. 1993; Bomans et al. 1996) or X-ray spectroscopy measurements of heavy elements (Fister et al. 2007). More recently, Menezes et al. (2014) used it in data analysis of integral field spectrograph from Gemini. To our knowledge, this is the first application of such a technique to the correction of instrumental broadening in spectra from RM observation.

We do not repeat the details of R–L deconvolution here, but just give a brief description (readers may refer to the original papers by Richardson 1972 and Lucy 1974). In short, if \( I_{\text{int}}^n \) is the \( n \)th estimate of the intrinsic profile in the iterative sequence, the \((n + 1)\)th estimate is obtained by

\[
I_{\text{int}}^{n+1}(\lambda) = I_{\text{int}}^n(\lambda) \int I_{\text{obs}}(\lambda) \xi(\lambda - \lambda') d\lambda',
\]

where

\[
I_{\text{obs}}^n(\lambda) = \int I_{\text{int}}^n(\lambda) \xi(\lambda - \lambda') d\lambda'.
\]

### 3.2. Line-broadening Function

During the spectroscopic exposures, we oriented the slit in order to simultaneously include the target and a nearby comparison star for their spectra (an object–star pair). It enables us to obtain the \( \xi \) of the object synchronously from the comparison star in the pair. To estimate the broadening function, we use the direct pixel-fitting method similar to that in Greene & Ho (2006) and Ho et al. (2009). The observed spectrum \( S \) of the comparison star is modeled by a stellar template spectrum \( T \) convolved by the broadening function:

\[
S(\lambda) = P(\lambda)[T(\lambda) \otimes \xi(\lambda)].
\]

Here, \( P \) is a polynomial that accounts for the large-scale mismatch in the continuum shape of the comparison star and template. In this work, we assume that \( \xi \) is a Gaussian function and select the most similar stellar spectrum from the Indo-U.S. Library of Coudé Feed Stellar Spectra (Valdes et al. 2004) to be the template of the comparison star. The selected templates for the comparison stars are listed in Table 1. In order to get the line-broadening function close enough to H\( \beta \), we set the fitting window to 4500–5500 Å in the rest frame of the objects. Prior to the fitting, the consecutive exposures of the object–star pair from each night are combined so as to provide high S/N. The best values of the FWHM and shift in \( \xi \) are determined by fitting the combined spectrum of the comparison star from each night via the Levenberg–Marquardt algorithm.

An example of an individual-night spectrum of the comparison star and the best model for Mrk 335 is shown in

![Figure 1. Flowchart of correction for line broadening.](http://www.noao.edu/ctlib/)
by applying $R$ of $\xi$ by the observation of Mrk 335 are shown in Figure 3. The FWHM, estimated in Paper I has been subtracted, as the arti
Figure 2. The distributions of the FWHM and shift of $\xi$ during the observation of Mrk 335 are shown in Figure 3. The FWHM, on average, is consistent with the mean value of 500 km s$^{-1}$ estimated in Paper I. However, through the fitting here, we are able to measure the broadening function on each individual night. For the other objects, the distributions of the broadening are similar to the case of Mrk 335, so we do not show them here. It should be noted that although SEAMBHs generally have weak $[\text{O} \text{iii}]$ at 5007, we can still try to estimate $\xi$ from the $[\text{O} \text{iii}]$ line in several objects with relatively strong and intrinsically narrow $[\text{O} \text{iii}]$ (e.g., Mrk 382) by comparing its width to the value of spectra with higher resolution (Whittle 1992), if we assume the narrow lines do not vary with time. The $\xi$ obtained from $[\text{O} \text{iii}]$ is consistent with the values estimated by the fitting here, and the differences are $\lesssim$50 km s$^{-1}$ on average.

After getting $\xi$ for each night (for each target), we reconstruct $I_{\text{obs}}$ by applying R–L deconvolution to the observed spectra $I_{\text{obs}}$ of the objects.

### 3.3. Iteration Number

The termination of iterations is one of the core issues in R–L deconvolution. Too few iterations are insufficient for reconstruction of the original signal, while an excess of iterations magnifies high-frequency noise and even produces nonsensical results (Lucy 1974). Here, a simple Monte Carlo approach is used to determine the appropriate number before terminating the iterations.

For each object, we first construct a Gaussian with the same FWHM and equivalent width (EW) as H$\beta$ in the observed mean spectra, where the mean broadening of 500 km s$^{-1}$ estimated in Paper I has been subtracted, as the artificial intrinsic spectrum. This artificial intrinsic spectrum is used to generate a mock observed spectrum $I_{\text{obs}}$ in each individual night by convolving with the $\xi$ obtained from the fitting in Section 3.2 and adding random noises with the same level of S/N as the observed spectrum. Then, we select the iteration number, which can get the best reconstruction (with the smallest $\chi^2$) of the artificial intrinsic spectrum by deconvolving $\xi$ from the mock $I_{\text{obs}}$, as the optimal number of iterations. The mock $I_{\text{obs}}$ is generated 20 times for each spectrum, and the median value of the optimal number of iterations obtained by the above procedure is chosen to be the final iteration number of the deconvolution.

### 3.4. Host Galaxy Subtraction

The spectra of AGNs and comparison stars are smeared by the same broadening function every night because both of them are point sources. However, the host galaxies of the objects are extended and their spectra are affected by broadening that is different from those of the comparison stars. Therefore, before de-convolving the spectra of AGNs with the broadening function obtained from the comparison stars in Section 3.2, the contribution of host galaxies should be removed. Paper III has already decomposed the spectra and extracted the contribution of host galaxies using the fitting scheme. We simply subtract those host contributions, which we obtained in Paper III, from the spectra of objects before deconvolution to avoid the potential influence of different broadening in host galaxies.

### 3.5. Monte Carlo Simulation on Deconvolution

We make use of Monte Carlo simulation to evaluate the robustness of reconstructing the intrinsic profile of the H$\beta$ line through the R–L deconvolution. We first create an artificial AGN spectrum by including (a) a power-law continuum, (b)
Fe II emission and broad He II, narrow emission lines of Hβ and [O III]λ 4959,5007, and a broad component of Hβ.

The components here are almost the same as the model we used in Paper III except for the absence of host galaxy contribution (the host does not influence the profiles of Hβ in the simulation). We set the FWHM and EW of Hβ in the artificial AGN spectrum to 1200 km s⁻¹ and 100 Å (see Figure 4), respectively, which are the typical values in the present sample.

In order to test the precision of recovery by deconvolution in the cases with various broadening and S/N values, we broaden the artificial spectrum by different broadening functions and add stochastic noise to generate the simulated observed spectra. In the meantime, we select a stellar spectral template (HD 44951 is used here) from the Indo-U.S. Library and broaden it with the same broadening as the AGN spectrum and add noise as well. We take the simulated observed AGN and star spectra

Figure 6. Comparisons of Hβ profiles between the input and output spectra in the Monte Carlo simulation. FWHM_{broadening} and Shift_{broadening} are the width and shift of the broadening function ξ. The dashed lines mark the values of (W20, W50, W80) and (C20, C50, C80) in the input artificial spectrum, while the dotted lines show their values in the convolved output spectra. The points are (W20, W50, W80) and (C20, C50, C80) of the profiles in the reconstructed spectra after the deconvolution. The colors show the S/Ns we set in the simulated observed spectra. The reconstruction is more successful in the cases of narrower broadening function and higher S/Ns.
as the input of the procedures in Section 3, and then compare the profiles of Hβ in the output reconstructed spectra to those of the original artificial AGN spectra.

To elaborate the comparison of profiles between the spectra before and after the deconvolution procedures, we define the full width at (20%, 50%, 80%) maximum as (W20, W50, W80), and centers at (20%, 50%, 80%) of maximum as (C20, C50, C80) to characterize the profiles of Hβ (please see Figure 5 for their definition). (W20, W50, W80) evaluate the width of the emission line at different heights, while (C20, C50, C80) show the shifts at the corresponding levels (see Figure 5). Here, W50 is simply the FWHM in the common sense. The comparison of emission-line profiles before and after the deconvolution in the Monte Carlo simulations is shown in Figure 6. Generally speaking, the deconvolution can recover the profile of Hβ correctly. The (W20, W50, W80) and (C20, C50, C80) of the reconstructed Hβ profiles are consistent with the value of the input artificial AGN spectrum in the cases with high S/Ns. The reconstruction is more successful in the cases with narrower broadening function and higher S/N, especially when the FWHM of the broadening is narrower than the input Hβ profile. The widths of Hβ in the observed spectra of SEAMBH2012 are 1000–2000 km s⁻¹, while the broadening is only ≈500 km s⁻¹. The S/N of the spectra in SEAMBH2012 is generally higher than 20. Therefore, the intrinsic profiles recovered by the deconvolution in Section 3 is reliable.

3.6. Profiles Before and After the Deconvolution

In order to give an overall evaluation of how effectively deconvolution works, examples of the comparison between the observed and deconvolved spectra of Mrk 335 are provided in Figure 7. It is very obvious that the deconvolution procedures correct the broadening and miscentering effect successfully. To further compare the profiles before and after the deconvolution, we measure the (W20, W50, W80) and (C20, C50, C80) of Hβ in the spectra before and after the deconvolution procedures. As an example, the values of Mrk 335 are shown in Figure 8. After the deconvolution, the widths (W20, W50, W80) of its Hβ lines become narrower by ∼(6%, 15%, 20%) on average. In particular, the distribution of W80 in the reconstructed spectra becomes much narrower meaning that the influence of broadening around the peak (the highest and narrowest part) of the emission line, which is more serious than in its wing (with broader width), has been corrected effectively. Additionally, the centers at different levels (C20, C50, C80) are more concentrated than in the cases before the deconvolution. Comparison before and after the deconvolution demonstrates the validity of the deconvolving procedures used in the present paper. The centers, it should be noted, are not located on 0 km s⁻¹ because the zero here is defined by the redshift queried from the NASA/IPAC Extragalactic Database.10

4. VELOCITY-RESOLVED TIME SERIES ANALYSIS

4.1. Methods

The light curves and the time delays between the variations of the continuum at 5100 Å and Hβ fluxes measured by simply integrating the full extent of the emission lines have been published in Papers I and II. Paper III updated these measurements by introducing a sophisticated scheme that fit AGN continuum, host contribution in the slit, and emission lines simultaneously. The updated time lags are consistent with the previous ones but have smaller uncertainties (see the comparison in Paper III). However, these time delays only stand for the radii averaged by the emissivity function of BLRs, and no information on velocity fields is carried out. In this section, we focus on the velocity-resolved analysis of delays in order to reveal the kinematics of BLR clouds in SEAMBHs.

The deconvolution procedures in Section 3 have removed the varying line broadening from the observed profiles and almost correctly the wavelength shifts caused by miscentering. After further correcting the remaining shifts (≤50 km s⁻¹) using the [O iii]λ5007 line as our wavelength reference, the spectra are ready for velocity-resolved time-series analysis. The rms (root of mean-square) spectra of the objects are obtained in the standard way from the spectra after the line-broadening correction. Similar to many previous works (e.g., Bentz et al. 2008, 2009b, 2010; Denney et al. 2009a, 2009b, 2010; Grier et al. 2013), we divide the Hβ emission line into several bins in velocity space, where each bin has equal amounts of flux in the rms spectrum. After integrating the flux of the emission line in each bin, we cross-correlate the obtained individual-bin light curves to the continuum light curve at 5100 Å. Due to the lack of error bars in the output spectra of the deconvolution, we estimate the uncertainties of the flux in the individual-bin light curves based on the differences between adjacent points using the median filter as in Paper I.

Figure 7. A comparison of the deconvolved profiles (Mrk 335) with the observed ones. The profiles are shifted vertically by a constant value (10⁻¹⁵ erg s⁻¹ cm⁻² Å⁻¹) from bottom to top for clarity. The broadening caused by instruments and varying seeing is corrected successfully. The miscentering caused by instruments and varying seeing is corrected successfully. The input of the procedures in Section 3, and then compare the profiles of Hβ in the output reconstructed spectra to those of the original artificial AGN spectra.

10 http://ned.ipac.caltech.edu/
The interpolation cross-correlation function (ICCF; Gaskell & Sparke 1986; Gaskell & Peterson 1987; White & Peterson 1994) is employed, and the centroid of the CCF, above 80% of the maximum cross-correlation coefficient ($r_{\text{max}}$), is adopted as the time lags (e.g., Koratkar & Gaskell 1991; Peterson et al. 2004; Denney et al. 2006, 2010; Bentz et al. 2009b and reference therein). The uncertainties in the measured lag time are determined through the Monte Carlo “flux randomization/random subset sampling” method described in Maoz & Netzer (1989) and Peterson et al. (1998, 2004). The rest-frame velocity-resolved time lags of the objects, as well as their rms

![Figure 8](image8.png)

**Figure 8.** A comparison of widths and shifts before and after the deconvolution (Mrk 335). Panels (a)–(f) are W80, W50, W20, C80, C50, and C20, respectively. The black solid lines are the distributions in the observed profiles, and the red dashed lines are the distributions in the reconstructed profiles after the deconvolution.

![Figure 9](image9.png)

**Figure 9.** Rest-frame velocity-resolved time delays and the corresponding rms spectra. The result for Mrk 335 obtained from the spectra without deconvolution is shown in the left plot, and its result from the deconvolved spectra is shown in the right one. The upper panel of each plot shows the centroid time lags in the divided velocity bins, and the lower panel is their rms spectrum (in units of $10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$). The red dashed lines are edges of the bins. The horizontal dotted line and the gray band mark the average time lag and the uncertainties provided in Paper III. The horizontal error bar in the upper panel denotes the velocity bin, while the vertical error bar is the uncertainty of the lag.
spectra created after deconvolution, are shown in Figures 9 and 10. The details of the objects are discussed below.

4.2. Individual Objects

Mrk 335. The Hβ emission line of this object is divided into eight bins in velocity space, where each bin contains 1/8 of the variable line flux in its rms spectrum. Its velocity-resolved time-series analysis (see Figure 9) demonstrates a clear gradient in the delays of the different velocity bins wherein the blueshifted part of the Hβ lags the response in its redshifted part (from ∼25 days in the blue end to ∼5 days in the red end). This kinematic signature is consistent with the expectation of inflow that the gas on the near side is receding from the observer while the gas on the opposite side is approaching the observer. In Figure 9, we also show the result before deconvolution. Generally speaking, the velocity-resolved time delays before and after the deconvolution are consistent with each other. However, the deconvolution-corrected result shows some details more clearly: the longer time delays in the blueshifted part vary gently while the lags in the redshifted part decrease more quickly. The before-deconvolution time lags only show a uniform gradient from blueshifted to redshifted velocity. In particular, the rms spectrum before the deconvolution contains relatively stronger contribution from the narrow Hβ emission line which is caused by the varying width of the narrow line (because of the changing broadening in each night), while this feature is much weaker in the rms spectrum of the reconstructed profiles. The comparison in Figure 9 also indicates that the deconvolution procedures can recover the velocity-resolved information moderately in RM time-series analysis.

Before our observation, Mrk 335 was monitored twice in 1989–1996 (Kassemberg et al. 1997; Peterson et al. 1998) and 2010–2011 (Grier et al. 2012), respectively. Its velocity-resolved time lags in the latter campaign have been published in Grier et al. (2013). It is not unexpected that the inflow signature in the velocity-resolved delays presented here is consistent with the previous measurements in 2010–2011 (Grier et al. 2013),
given the short time interval between these two campaigns. Such a signature has also been reported in the velocity-resolved delay analysis of many other sources like Arp 151 (Bentz et al. 2008, 2009b), NGC 3516 (Denney et al. 2009a, 2010), Mrk 1501 (Grier et al. 2013), and PG 2130 + 099 (Grier et al. 2013).

Mrk 142. The velocity-resolved time delays of Mrk 142 are reported here for the first time. It was previously monitored by the LAMP collaboration (Bentz et al. 2009b); however, the authors do not show its velocity-resolved lags perhaps due to their data quality. The observation in our campaign has a more homogeneous cadence and better calibration precision. Opposite to the case of Mrk 335, Mrk 142 shows signature of outflow indicated by the shorter time lag from BLR gas in the blueshifted side of the Hβ line compared with the gas in the redshifted side. Interestingly, to our knowledge, the signature of the outflow was observed distinctly by RM in only one case, NGC 3227 (Denney et al. 2009a, 2010), before the detection shown here. Compared with the low accretion rate in NGC 3227 (Denney et al. 2010; Paper IV), Mrk 142 is an SEAMBH and radiation pressure acting on the ionized gas is probably the driver for the observed outflow.

Mrk 486. It also demonstrates a clear signature of infalling gas as in the case of Mrk 335. Except for the first bin, the response to the continuum variation in the blueshifted gas lags the response of the gas corresponding to the redshifted side.

Mrk 1044. The velocity-resolved lags of Mrk 1044 are relatively symmetric and show evidence of simple virialized motions and that high-velocity gas is located in the more central region, which is similar to the cases of NGC 5548 (Denney et al. 2009a), SBS 1116 + 583A (Bentz et al. 2009b), Mrk 1310 (Bentz et al. 2009b), NGC 4051 (Denney et al. 2009b, 2010), and 3C 120 (Grier et al. 2013) in the previous works.

MCG +06-26-012. Outflow signature is seen in this object: the time delays (∼20 days) in the blue part of Hβ are slightly shorter than those (∼30 days) in the red part. However, the outflow signs are a little bit ambiguous because of the large errors. The large error bars are caused by the inhomogeneous sampling and the short monitoring period compared with the
variation in the light curves. MCG +06-26-012 is the only sub-Eddington object in the present sample (see details in Paper II).

Mrk 382. The lags in the different velocity bins are indistinguishable. This phenomenon has been found in other objects, such as Mrk 1310 (Bentz et al. 2009b), NGC 5548 (Bentz et al. 2009b), and Mrk 290 (Denney et al. 2010). This may either be caused by the fact that the lag differences among the bins are smaller than their error bars (due to the quality of the current data), or it could be real intrinsically that those bins have the same time lags. If the line of sight velocity remains constant in the BLR, the motions of the clouds are fully chaotic. This remains open for future observations with high quality data.

IRAS F12397 + 3333 and Mrk 493 are similar to Mrk 382. IRAS 04416 + 1215. The direct integrating method in Papers I and II failed to give the average time lag of its integrated Hβ emission-line flux. Only the multi-component fitting method in Paper III is able to detect its delay. Here, we adopt the direct integrating method to measure the light curves after the division of the bins and still fail to get a reliable detection of its velocity-resolved lags. We divide its Hβ into two bins and demonstrate the result here for completeness. The r_max in the redshifted bin is only ~0.4.

5. DISCUSSIONS

The outflows suggested by the observation of blueshifted broad absorption lines are not rare in AGNs (e.g., Trump et al. 2006; Gibson et al. 2009 and reference therein). However, how the outflows contribute to broad emission lines, especially in high accretion rate AGNs, is still subject to some debate. Considering that super-Eddington accreting AGNs probably have the strongest radiation pressure, which can provide kinetic energy to BLR gas, among the entire AGN population, the possibilities of outflows occurring in SEAMBHs are doubted to be higher than sources with normal accretion rates. However, the present sample, although limited in size, shows diverse properties of the BLR kinematics, rather than simple outflows (there is only one from the four detected SEAMBHs, except for MCG +06-26-012, with low accretion rate). It is consistent with the fact that the observed profile of Hβ in the present sample does not show a unified signature of blueshifted asymmetry. On the other hand, there are a few objects (two out of four super-Eddington AGNs) showing clear evidence for the presence of infalling gas in BLRs. Considering the fact that objects in the present sample are super-Eddington accreting AGNs, the velocity fields of the surrounding gas showing infall in kinematics are not surprising. Otherwise, a significant fraction of the accreting gas will be channeled into outflows, suppressing the fast growth of less massive black holes. It is impossible to reach a conclusion about the pattern of velocity fields of ionized gas in the vicinity of black holes in super-Eddington accreting AGNs. We hope increased monitoring of SEAMBHs and normal AGNs could clarify the patterns of the velocity fields.

6. CONCLUSIONS

We have presented here velocity-resolved time lag measurements of nine objects observed in our SEAMBH2012 campaign. To correct the line broadening caused by instruments and seeing, we use R-L deconvolution to reconstruct the Hβ profiles. The broadening function in each night is estimated by fitting the spectra of the stars observed simultaneously with stellar templates, and the Monte Carlo method is adopted to test the validity of the broadening-correction procedures. We show that the R-L iteration is an efficient method to recover the velocity-resolved information to some extent.

All of the objects in the present sample are NLS1s with very high accretion rates except for MCG +06-26-012. Five sources among them demonstrate clear velocity-resolved time delays in their Hβ emission lines. The velocity-resolved lags of Mrk 335 and Mrk 486 show the signature of gas infall, while the BLR clouds in Mrk 142 and MCG +06-26-012 tend to be radially outflowing. The symmetric pattern of Mrk 1044 is consistent with virialized motions. The time lags of the four other objects are not velocity-resolvable. We do not find significant differences in the BLR kinematics of SEAMBHs compared with sub-Eddington AGNs. Some discussions on the result of each individual object are provided in the main text. This analysis provides new insight into the geometry and kinematics of BLRs in SEAMBHs.

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