REVERBERATION MAPPING WITH INTERMEDIATE-BAND PHOTOMETRY: DETECTION OF BROAD-LINE H\textalpha TIME LAGS FOR QUASARS AT 0.2 < z < 0.4

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ABSTRACT

We present a reverberation mapping (RM) experiment that combines broad- and intermediate-band photometry; it is the first such attempt targeting 13 quasars at 0.2 < z < 0.9. The quasars were selected to have strong H\textalpha or H\beta emission lines that are located in one of three intermediate bands (with FWHM around 200 Å) centered at 8045, 8505, and 9171 Å. The imaging observations were carried out in the intermediate bands and the broad i and z bands using the prime-focus imager 90Prime on the 2.3 m Bok telescope. Because of the large (∼1 deg\textsuperscript{2}) field of view (FOV) of 90Prime, we included the 13 quasars within only five telescope pointings or fields. The five fields were repeatedly observed over 20–30 epochs that were unevenly distributed over a duration of 5–6 months. The combination of the broad- and intermediate-band photometry allows us to derive accurate light curves for both optical continuum emission (from the accretion disk) and line emission (from the broad-line region, or BLR). We detect H\textalpha time lags between the continuum and line emission in six quasars. These quasars are at relatively low redshifts 0.2 < z < 0.4. The measured lags are consistent with the current BLR size–luminosity relation for H\beta at z < 0.3. While this experiment appears successful in detecting lags of the bright H\alpha line, further investigation is required to see if it can also be applied to the fainter H\beta line for quasars at higher redshifts. Finally we demonstrate that, by using a small telescope with a large FOV, intermediate-band photometric RM can be efficiently executed for a large sample of quasars at z > 0.2.

Key words: galaxies: active – quasars: emission lines – quasars: general – quasars: supermassive black holes

Supporting material: data behind figures

1. INTRODUCTION

Reverberation mapping (RM; Blandford & McKee 1982; Peterson 1993) of an active galactic nucleus (AGN) measures the light travel time (i.e., lags) between different regions of an AGN, most commonly the time lag between the UV/optical continuum (from the accretion disk) and the broad line (from the broad-line region, or BLR) emitting regions. RM is a powerful tool for probing the structure and kinematics of AGN BLRs. RM is used to estimate the masses of central supermassive black holes (SMBHs) in an AGN, by combining the relation between the BLR size and AGN luminosity (the R–L relation) with the assumption of virialized motions of clouds in the BLR. Through application of this method, RM has been established as the primary direct technique for estimation of SMBH mass for AGNs/quasars at z ≲ 0.1.

RM campaigns are expensive and time-consuming. They require repeated observations of individual targets with sufficient cadence over durations of a few months to a few years, depending on the source redshift and luminosity. The success rate also relies on other factors, such as whether the variability of the target is significant or not during the RM campaign, which is usually unpredictable. To date, RM experiments have been successful for about 60 AGNs/quasars (e.g., Kaspi et al. 2000, 2005; Peterson et al. 2002, 2004, 2014; Bentz et al. 2009, 2013; Denney et al. 2009, 2010; Barth et al. 2011, 2015; Rafter et al. 2011, 2013; Du et al. 2014, 2015; Wang et al. 2014; Hu et al. 2015). A more detailed history of AGN RM experiments is summarized in a few recent works (e.g., Bentz et al. 2013; Peterson 2014; Bentz 2015; Shen et al. 2015a).

The majority of the above RM work was done with low-redshift AGNs at z ≲ 0.2. AGNs/quasars with much higher redshift (z ≥ 1) have also been tried (e.g., Metzroth et al. 2006; Kaspi et al. 2007; Trevese et al. 2007), yet the number of the successful detections of time lags is still very small. Recently the SDSS Reverberation Mapping program (SDSS-RM; Shen et al. 2015a) has enabled a new method of carrying out RM experiments. The SDSS-RM program is a dedicated multi-object RM campaign that simultaneously targeted 849 quasars in a single 7 deg\textsuperscript{2} field. Based on the SDSS-RM data, Shen et al. (2015c) have reported their first detections of time lags in a sample of quasars at z ≥ 0.3.

Traditional RM programs use spectroscopic observations to monitor the variability of continuum and line emission. Recently, photometric RM has been proposed or performed (e.g., Haas et al. 2011; Chelouche & Daniel 2012; Zu et al. 2013; Chelouche et al. 2014). The basic idea is to take photometry in two bandpasses, with one bandpass “on” an emission line and the other one “off” the line. The combination of the two measurements is used to derive the continuum and line fluxes. The advantage of the photometric RM is that it does not require spectroscopic observations, and can be easily performed with small telescopes. The challenge is the small contribution of the emission line flux to the total bandpass flux within a broad band, so that the photometric uncertainties significantly hamper measurements of variability in the line...
fluxes. Alternatively, one may use a narrow band with a FWHM of a few tens of Å (up to ~120 Å) to cover the emission line. This has been done for a few local AGNs at $z < 0.05$ (e.g., Haas et al. 2011; Ramolla et al. 2013; Pozo Nuñez et al. 2015). In this case, the line flux contributes a large fraction of the total flux in the narrow band, and line variability is more readily detected.

In this paper we present our intermediate-band reverberation mapping (IBRM) project, which uses the combination of broad and intermediate bands (with FWHM around 200 Å) to perform photometric RM. The usage of intermediate bands has the following two advantages, in addition to the general advantages of photometric RM mentioned above. An intermediate band can usually cover a whole emission line, while the line flux still contributes a significant fraction of the total flux in the band, if the line is selected to have high equivalent width (EW) as we do for the IBRM program. Second, it has a larger (compared to narrow bands) dynamic range in wavelength that allows the inclusion of more than one target per field, which substantially increases observing efficiency. In our IBRM program, we observed 13 quasars within five fields or telescope pointings, and successfully detected time lags in six of them.

The structure of the paper is as follows. In Section 2 we present our quasar sample selection and their optical spectra. In Section 3 we introduce our IBRM campaign and the details of observations and data reduction. We derive the light curves and time lags of the quasars in Section 4, and put them in the context of the $R$–$L$ relation in Section 5. In Section 6 we summarize the paper. Throughout the paper we use a $Λ$-dominated flat cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $Ω_m = 0.3$, and $Ω_Λ = 0.7$. All magnitudes are in the AB system.

2. QUASAR SAMPLE

In this section we present the selection of our quasar sample. Before we go into the detailed steps, we briefly introduce the telescope and instrument that we used for the IBRM project, which is directly related to our sample selection. The telescope that we used is the 2.3 m Bok telescope at the Steward Observatory, and the instrument is its prime-focus imager 90Prime. 90Prime has a large, square field of view (FOV) of roughly one degree on a side. It uses four $K$ thin CCDs that were optimized for U-band imaging (Zou et al. 2015). We used two broad-band filters, $i$ and $z$, and three intermediate-band filters, BACT12, BACT13, and BACT14. These intermediate-band filters were originally designed for the Beijing–Arizona–Taipei–Connecticut (BATC) Color Survey (e.g., Fan et al. 1996; Yan et al. 2000; Zhou et al. 2001). The broad-band filters are used to measure continuum flux. The effective wavelengths of the three intermediate-band filters are 8045, 8505, and 9171 Å, with FWHMs of 230, 180, and 264 Å, respectively. They cover three wavelength ranges with relatively weak OH sky emission, so imaging in these bands is very efficient.

2.1. Sample Selection

Our sample selection began with the SDSS DR7 quasar catalog delivered by Schneider et al. (2010) and Shen et al. (2011). The emission lines used for our IBRM project are $H_α$ and $H_β$, two of the strongest lines in quasar spectra. We first selected quasars at certain redshifts so that their $H_α$ or $H_β$ emission lines are located in one of the three intermediate bands (the center of an emission line is roughly within the central 50% of the filter). Specifically, the redshift ranges considered here are [0.216, 0.236], [0.290, 0.302], [0.385, 0.410], [0.642, 0.668], [0.741, 0.758], and [0.870, 0.904], and there are 4326 quasars in these redshift ranges. We then selected quasars in a certain coordinate range, because the observations of our IBRM project shared the Bok nights with the SDSS-RM project (Shen et al. 2015a), as we will see in the next section. The coordinate range chosen here is $8$ hr $< R.A. < 13$ hr and decl. $> 25°$, and 1227 quasars passed this selection. We further selected targets in a certain brightness range (namely, $17 < i < 19.5$ mag) with high $H_α$ or $H_β$ EW. The $H_α$ and $H_β$ EW values were measured from the SDSS spectra and taken from Shen et al. (2011). We required that the observed $H_α$ EW was greater than 180 Å, or the observed $H_β$ EW was greater than 90 Å. This ensures that the line emission contributes a significant fraction of the total flux in the intermediate bands. This is one of the keys for the success of this program. The choice of $i < 19.5$ mag was to ensure that we can get high signal-to-noise ratios ($S/N$) in the intermediate bands with an integration time of 5 minutes. The choice of $i > 17$ mag was to select quasars with expected time lags (in the observed frame) shorter than the duration of our observing campaign (roughly 5–6 months). The expected time lags for most of the selected quasars are between 20 and 60 days. The observed-frame time lags also depend on redshift due to the time dilation of $1 + z$ and the strong dependence of the intrinsic luminosity on redshift for a given apparent magnitude. Therefore, for very bright quasars at relatively high redshifts ($z \geq 0.6$), their expected time lags could be significantly longer and even close to the duration of our RM campaign. We selected 622 quasars in this step.

After we obtained the list of the quasars from the above steps, we chose the area/fields that have more than one quasar per square degree (the FOV of the 90Prime). This was to increase the efficiency of the project. Meanwhile, we matched the quasars to the preliminary catalog of Pan-STARRS1 (PS1; Schlafly et al. 2012; Tonry et al. 2012; Magnier et al. 2013), and obtained their variability values as follows. For each quasar, we extracted the standard deviations of the magnitudes from the catalog. There are five standard deviation values for five PS1 bands ($g'_{P1}$, $r'_{P1}$, $i'_{P1}$, $z'_{P1}$, and $y'_{P1}$), and we took the average of the second and third largest standard deviation values as the variability of this quasar. We then eliminated ~10% of the sources whose variability was roughly consistent with error bars. Finally, from the remaining sources we selected 13 quasars or five fields for the IBRM project, by considering the following: (1) the fields are roughly evenly distributed between 8 and 13 hr R.A. for the convenience of observations; (2) the quasars have relatively strong $H_α$ or $H_β$ EWs (stronger are better); (3) the quasars show relatively strong variability. When the demands for (2) and (3) are difficult to meet simultaneously, we slightly favored (2) because quasar variability is a stochastic process.

Table 1 lists the details of the 13 quasars. Column 1 shows the ID of the quasars. We use “F1” to “F5” to denote the five fields, and use “a” to “c” to denote the quasars within a field. The following four columns are the coordinates, redshifts, and $i$-band magnitudes drawn from the SDSS DR7 catalog. Columns 6 and 7 show the emission lines that we used and their EWs in the observed frame. Column 8 shows the...
intermediate filters that cover the lines. These quasars cover a redshift range of $0.22 < z < 0.88$. We mainly use the H$\alpha$ line (10 out of 13 quasars), because it is much stronger than the H$\beta$ line, and thus quasars with strong H$\alpha$ were preferentially selected. Note that the EW of F1b is lower than our selection criterion. This is because the line is close to the red end of its SDSS spectrum, and the EW value given by the SDSS DR7 is not accurate. The value given in the table was measured from the SDSS spectrum, and the EW value given by the SDSS DR7 is slightly different from those of the SDSS $i$ and $z$ filters.

In several cases, the intermediate bands do not entirely cover the emission lines (e.g., F2a and F5b). The effect of missing line wings on the measurement of BLR sizes is very small. When we calculate line emission for light curves in Section 4, we consider only the contribution from the part covered by the intermediate bands, which contains more than 90% (in most cases more than 95%) of the total line flux. Pozo Nuñez et al. (2014) conducted detailed calculations to estimate the consequences of the above missing line wings on photometric RM results, and concluded that the effect on the measurements of BLR sizes is only a few percent. This is negligible compared to the uncertainties in size measurement we will get in Section 4.

2.2. Optical Spectra

Single-epoch quasar optical spectra are needed to accurately derive the line contribution to the broad-band photometry. These quasars have optical spectra from SDSS I and II. The SDSS spectra do not cover the wavelength range beyond $\sim9100$ Å, which is needed for the BATC14 filter. For the quasars observed with the BATC14 filter (see Table 1), we obtained new optical spectra using the MMT Red Channel spectrograph. The observations were carried out as backup targets during other programs in 2014, when weather conditions were poor. The observations were made in longslit mode with a spectral resolution of $\sim10$ Å. The integration time was roughly 5–10 minutes per object, which is sufficient for our purposes. The spectra were reduced using standard IRAF routines. The MMT spectra cover a wavelength range of 7000–10,000 Å. The final spectra of these quasars are the combination of the SDSS and MMT spectra.

Figure 1 shows the optical spectra of our quasar sample in the observed frame. As we mentioned above, some spectra were directly taken from the SDSS, while the others were the combination of the SDSS and MMT spectra. In each panel of Figure 1, we also show the transmission curves of the 90Prime $i$ and $z$ filters (the blue dotted profiles) and one of the intermediate filters (the red dotted profile) that cover H$\alpha$ or H$\beta$. The CCD quantum efficiency has been taken into account.

Note that the transmission curves of the 90Prime $i$ and $z$ filters are slightly different from those of the SDSS $i$ and $z$ filters.

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3. OBSERVATIONS AND DATA REDUCTION

The IBRM project was carried out in the spring semester, 2014. It shared the Bok nights with the SDSS-RM project. As we mentioned earlier, the SDSS-RM project was one of the SDSS III ancillary projects. It used the CFHT and Bok telescopes to do broad-band ($g$ and $i$) photometry for measurements of continuum light curves in SDSS-RM (Shen et al. 2015a). Our targets and observing time were coordinated with the SDSS-RM project.

3.1. Bok Observations

The Bok observations of the quasars were conducted in 2014 January through June. Due to the constraints from the telescope scheduling, we obtained one or two long observing blocks each month (see Section 4.1). Hence the Bok nights for the SDSS-RM and IBRM projects were not evenly distributed, and were clustered around the nights with relatively bright moon phase. Such an observing schedule does not provide an optimal cadence for RM studies. Each of the five fields was observed for between 20 and 30 epochs over the full campaign.
or fields from F1 to F5. We usually observed at least three fields per epoch/night. The observations were made via observing scripts. Each time after we slewed the telescope to a new field, the scripts automatically changed filters, tweaked focus, and took the data, in the order of $i$, $z$, BATC12, BATC14 (and BATC13 for Field 4). The typical on-source integration time was 150 s in the $i$ band, and 300 s in the other bands. The observing conditions were mostly moderate with clear skies, moderate seeing (~1.5), but significant moonlight.

3.2. Data Reduction

The 90Prime images were reduced in a standard fashion using our own IDL routines. The basic procedure was described in Jiang et al. (2015). First, we made a master bias
image and a master flat image from bias and flat images taken on the same night. A bad-pixel mask was also created from the flat image. Science images were then corrected for overscan and bias and flat-fielded. Next we identified saturated pixels and bleeding trails, and incorporated them (along with the bad-pixel mask) into the weight images. The affected pixels were interpolated over in the science images. We call the science images at this stage “corrected images.”

The 90Prime CCDs are thin chips, and thus produce strong fringing in the bands that we used. We subtracted sky background and fringes using two iterations. The first round of sky subtraction was performed by fitting a low-order 2D polynomial function to the background. A master fringing image (per filter) was made by median stacking at least eight sky-subtracted images in the same filter. This fringing image was scaled and subtracted from the original “corrected” images (before sky subtraction was done). We detected objects in the fringe-subtracted images using SExtractor (Bertin & Arnouts 1996). A better sky image was produced from each fringe-subtracted image with the detected objects masked out. Then the second round of sky and fringe subtraction was performed, but with the detected objects masked out.

In order to derive astrometry, we detected bright objects using SExtractor (Bertin & Arnouts 1996), and calculated astrometric solutions using SCAMP (Bertin 2006) by matching objects to the SDSS. With the new astrometry we remapped the images using SWARP (Bertin et al. 2002). The remapped images have a native pixel size of 0".455.

3.3. Photometry

Accurate (relative) photometry is another key to the success of this project. In order to achieve accurate photometry, for any given quasar in the whole observing campaign, we used a large number of nearby bright point sources for photometric calibration. These bright sources and our quasar targets were always located in roughly the same part of the same CCD, which minimizes the effect from any large-scale systematics. This allows us to achieve relatively small uncertainties (∼0.01 mag) on the magnitude zero points that are usually negligible compared to the uncertainties in the light curves that we derive in Section 4. The details are as follows.

The four CCDs were read out via 16 amplifiers, with four amplifiers per CCD. For any of the 13 quasars in an image, we performed photometry only for the amplifier area in which this quasar was located (roughly 15" on a side). We did not use other parts of the image (for this quasar) due to the possible small zero-point shift across the amplifiers and CCDs (Zou et al. 2015).

We first chose a “standard” night, which was photometric and relatively dark, and performed photometry for the images taken on this standard night. Photometry was measured within an aperture (diameter) size of eight pixels (∼3"6) using SExtractor. We then picked up bright (at least 30σ detection) but unsaturated point sources and matched them to the SDSS. The density of the bright stars is about 50–100 per amplifier. We used the SDSS point-spread function (PSF) magnitudes, so the measured magnitudes are total magnitudes with aperture corrections automatically taken into account. After we obtained the i- and z-band magnitudes for a given object, we calculated its intermediate-band magnitudes as follows. We assumed that its spectrum in the wavelength range of the i and z bands (which also covers the three intermediate bands) was a power law, which is determined by its i- and z-band magnitudes. Then its intermediate-band magnitudes were directly calculated from this power-law spectrum and the intermediate-band transmission curves. The resultant magnitudes have very weak dependence (usually Δm ≲ 0.03 mag) on the assumption of the shape of the spectrum, as long as there are no emission or absorption lines in the intermediate bands. Such small uncertainties on the zero-magnitude points have no effect on our measurements of light curves, which rely on relative photometry. We calculated AB magnitudes for all these bright stars taken on the standard night. These bright stars were used as standard stars for all other images.

We then measured photometry for the images taken on all other nights. The procedure was the same. But we used the bright stars found on the standard night as “standard stars,” and used their magnitudes for absolute flux calibration. Because of the large numbers of bright standard stars for any given quasar, we achieved high accuracy on relative zero flux points. Figure 2 illustrates this point. Its horizontal axis shows the magnitude difference of the standard stars taken between the standard night and the first several nights other than the standard night. The vertical axis shows the normalized distribution of the magnitude difference. The standard deviation (σ) values were estimated by fitting a Gaussian profile (the red profiles) to the top 80% of the distributions (the bottom 20% deviates significantly from the Gaussian distribution). The tight distributions in the four bands suggest that our flux calibration is very accurate.

![Figure 2](image-url)
Figure 3 shows the measurement uncertainties as a function of total magnitude for all quasars observed in the whole RM campaign. The errors are measured within an aperture (diameter) size of eight pixels. The uncertainties from absolute flux calibration are not included. The errors are mostly smaller than 0.02 mag. In rare cases, errors can be larger than 0.05 mag as a result of low sky transparency.

4. TIME LAGS

In this section we present our main results. For each quasar in Table 1, we first compute the light curves for the continuum and emission line. This step is straightforward, because we have decent optical spectra and accurate broad- and intermediate-band photometry. We then derive the time lag between continuum and line emission in standard ways.

4.1. Light Curves

For each quasar we have a single-epoch optical spectrum and a series of $i$, $z$, and intermediate-band photometric measurements. We first calculate the contribution of the line emission (or equivalently the contribution of the continuum emission) to the broad-band photometry using the optical spectrum. We select regions with little line emission in the spectrum as continuum windows, and fit a power-law curve ($f_{\lambda} = b \times \lambda^{-\alpha}$) to these windows. This power-law continuum may contain a central AGN component and a host galaxy component (see the next section). As long as the host galaxy does not vary (a constant component), the inclusion of the host galaxy component does not affect the determination of time lags. The line emission is obtained by subtracting the power-law continuum from the spectrum. We assume that the contribution of the line emission to the broad-band photometry does not vary with time. The reason is that the line contribution is smaller than 5%, and the line variability is usually smaller than 20%, so the effect of line variability on broad-band photometry is smaller than 1%. As we will see below, the continuum value we derive for a quasar is determined by two broad bands ($i$ and $z$), with one band without line contamination, so the effect of line variability on continuum is even smaller by roughly a factor of two, which is much smaller than the uncertainties in the light curves derived below. Thus our above assumption has a negligible effect on the measurement of the continuum, but largely simplifies our procedure.

We then derive the line flux and continuum flux at the wavelength of the intermediate band from their corresponding $i$, $z$, and intermediate-band photometry at each epoch. The continuum components at $i$ and $z$ are computed by subtracting the line contribution from these bands. A power-law continuum is derived analytically from the two flux measurements at the effective wavelengths of the $i$ and $z$ bands. We then determine the continuum value at the effective wavelength of the intermediate band from the power-law continuum. This continuum value is the continuum that will be used for light curves. Finally the line emission is obtained by subtracting the continuum component from the intermediate-band photometry.

Figure 4 plots the light curves of the six quasars that show significant time lags during our IBRM campaign (see the next subsection). For each object, the upper panel shows the light curves in the $i$ (blue circles), $z$ (green circles), and one of the intermediate bands (red circles). The lower panel shows the light curves of the continuum flux (upper curves) and line flux (lower curves).

4.2. Lag Measurements

We estimate time lags between the line and continuum emission derived above using the JAVELIN package (Zu et al. 2011, 2013). As we have seen, the light curves were unevenly (sometimes sparsely) sampled, due to the constraints from scheduling of telescope time. JAVELIN is able to deal with
such an uneven sampling. It assumes that the variability of a quasar/AGN can be well described by the damped random walk (DRW) model (e.g., Kelly et al. 2009), and the light curve of its emission line is the lagged and scaled version of its continuum light curve. For a given quasar, we first model its continuum variability using JAVELIN, and find the distribution of the DRW parameters. We then statistically interpolate the continuum light curve. The light curve is shifted, smoothed, and scaled, before it is compared to the corresponding emission-line curve. The smoothing here refers to the use of a transfer function (non-delta-function) in JAVELIN to mimic the realistic line response to continuum light curves. This is due to the fact that the BLR clouds are distributed at different radii with different velocities, which results in a transfer function that is broad in lag. For details, see the JAVELIN papers (Zu et al. 2011, 2013). This process is performed 10,000 times using the Markov chain Monte Carlo method. The final results are the best model fits for each try. Note that all calculations above are based on flux (not magnitudes).

Based on the measurements of time lag from JAVELIN, we find that six (out of 13) quasars in our sample show clear lag detections during our IBRM campaign (we will discuss the other quasars in the next subsection). The lag range allowed in the above calculation is from $-100$ to $+100$ days. We do not consider a wider range, simply because the duration of the IBRM campaign was only 150–170 days. Figure 5 shows the

Figure 4. Light curves of the six quasars that show significant time lags during our IBRM campaign. For each object in the upper panel, the blue and green circles show the light curves in the $i$ and $z$ bands, and the red circles indicate the light curve in the intermediate band. The lower panel shows the light curves of the continuum flux (upper curves) and line flux (lower curves). See Section 4.1 for details on how the line and continuum flux is derived. These two curves have been shifted along the $y$ axis so that they are displayed clearly. The gray shaded curves indicate the simulated light curves ($1\sigma$ area) as computed from JAVELIN (Section 4.2). The data used to create this figure are available.
distributions of the measured lags for the six quasars (their light curves are shown in Figure 4). They show clear single-distribution peaks. The results are listed in Table 2. The lag errors in the table are calculated by including 16% and 84% of the total distributions around the median distribution (50% of the total). Obviously they depend on the lag range that we consider. On the other hand, they are not sensitive to the lag range, as long as the lag detections are substantial with most distributions clustered around the median values. This applies to all quasars except F2b in Figure 5. The lag measured for F2b is 21.4 ± 8 days. It has a large upper error due to the non-negligible fraction of the total distribution beyond 70 days. If we were to reduce the lag range to between −100 and 70, the lag becomes 21.2 ± 7 days, with a much smaller upper error. We adopt the larger error for consistency in the paper.

We further use the discrete correlation function (DCF) to validate the above lag detections. The algorithm we adopt is the z-transformed DCF (zDCF), which was designed to handle unevenly sampled light curves (Alexander 2013). The estimated DCFs for the six quasars are shown in Figure 6. These quasars also show clear DCF peaks. The lag uncertainties from the zDCF are larger. One reason is that the zDCF uses time-lag bins, and the minimum number required in each bin is roughly 11 for meaningful statistics in the zDCF. Given the small numbers of epochs in our IBRM project, the zDCF can only coarsely sample the light curves in the lag time space. Nevertheless, the zDCF peaks in Figure 6 are consistent with the results from JAVELIN except for F2b. F2b shows a significant lag detection by JAVELIN in Figure 5, but its zDCF peaks at ∼0. The lag detection from JAVELIN could be real, or a false positive because of the sparse sampling in light curves. On the other hand, the zDCF of F2b is broad, which is not against a lag of ∼20 days. This can be solved with more evenly and finely sampled light curves in the future.

Figure 5. Time lags (in the observed frame) for six quasars with significant lag detections. The lag distribution for each quasar is based on 10,000 experiments using JAVELIN (Zu et al. 2011). See Section 4.2 for details. The distributions have been normalized so that the peak values are equal to 1.

Figure 6. DCFs for the six quasars with significant lag detections (in the observed frame). The DCFs are estimated using the zDCF (Alexander 2013). The dotted vertical lines indicate the lags measured from JAVELIN (Table 2 or Figure 5). The results from the zDCF and JAVELIN are consistent.

We perform a simple experiment to test our results. For any pair of light curves (continuum and line) in the six quasars, we randomly reorder one curve, and repeat the above processes using JAVELIN to estimate the rate of false positives. This is done a hundred times for each quasar (each pair of light curves). These tests generally show small false-positive rates. For the first four quasars that were observed in nearly 30 epochs, the false-positive rates are only 3%–4%. The rates increase to 7%–9% for the last two quasars that were observed only ∼20 times (see Shen et al. 2015c for a detailed discussion).

The detected lags in the six quasars are all for Hα, and at relatively low redshifts between 0.22 and 0.40. This is not surprising, because 10 out of the 13 lines in the original sample are Hα, and Hα is much stronger than Hβ on average. In addition, higher redshifts usually mean higher intrinsic luminosities and larger time dilation (1 + z), leading to much larger observed time lags that are likely beyond the detection capability of our IBRM campaign.

### Table 2

| ID   | Redshift | Lag (days) | Log(L/1) | f_{host} |
|------|----------|------------|----------|----------|
| F2b  | 0.233    | 21.4^{+8.3}_{-4.8} | 43.84     | 0.21     |
| F3b  | 0.398    | 42.2^{+4.8}_{-3.6}  | 44.17     | 0.19     |
| F3c  | 0.229    | 34.0^{+11.7}_{-11.1}| 43.84     | 0.37     |
| F4a  | 0.401    | 38.1^{+12.8}_{-11.8}| 44.32     | 0.28     |
| F5b  | 0.235    | 25.0^{+13.3}_{-10.3}| 43.79     | 0.22     |
| F5c  | 0.229    | 37.9^{+10.3}_{-7.4} | 44.25     | 0.36     |

Note. The time lags are in the observed frame. The quasar luminosities (in units of erg s$^{-1}$) have been corrected for host galaxy contamination. The last column shows the contribution from host galaxies (Section 5.1).
4.3. Quasars without Significant Lag Detections

We did not detect time lags between continuum and line emission in the other seven quasars in our sample. Similar to Figure 6, Figure 7 shows the distributions of the lags for these quasars from JAVELIN. Unlike those in Figure 6, quasars in Figure 7 do not show single strong peaks. They rather show multiple peaks or continuous distributions. There are two main reasons for these non-detections. The first reason is that the expected time lags based on the current $R$–$L$ relation (e.g., Bentz et al. 2013) are comparable to the duration of our campaign. For example, the lags expected for F1b, F3a, and F4c are greater than 120 days, primarily due to their high redshifts. The second reason is that the variability is small, or that the light curves are relatively flat. These quasars show moderate to large variability in the PS1 data. But quasar variability is a stochastic process, and past large variability does not guarantee large variability in the future. In addition, large gaps in light curves can often cause aliasing, and this to be seems the case for F4c. For these objects, our data were insufficient to detect lags.

5. BLR SIZE–LUMINOSITY RELATION

5.1. Light from Host Galaxies

Quasar host galaxies may contribute a significant fraction of the total light in the bands that we measured. There are two general methods to estimate the light from the hosts: image decomposition and spectral decomposition. We do not have the high S/N spectra that spectral decomposition requires (e.g., Shen et al. 2015b), so we rely on image decomposition. Image decomposition works better on images with better PSFs (or seeing). The site of the Bok telescope does not deliver good seeing, and the average PSF size of our images is about 1′′.5. In order to construct a deep combined image with a decent PSF for each quasar, we choose 50% of the $i$-band images with the best PSF sizes, and co-add them to a stacked image. The reason to choose the $i$ band is twofold. One is that it is the deepest band. The other is that its effective wavelength is close to the rest-frame 5100 Å (the commonly used wavelength) for our quasars. As for flux calibration, we consider only 1/16 of the image, i.e., the amplifier that the quasar is located in. This is to avoid any possible large PSF variation across the large FOV. The PSF sizes of the combined images are about 1′′.1, which is good enough for image decomposition on low-redshift quasars (e.g., Matsuoka et al. 2014).

We perform image decomposition on the combined $i$-band images. For each quasar/image, the detailed steps are as follows. We first derive a PSF model for the quasar using PSFex (Bertin 2011). PSFex finds point sources in the image, and builds PSF models as a function of position. We take the PSF model that is closest to the quasar position as the PSF model for the quasar, although the PSF variations are quite small across a single amplifier in our images. The PSF image size is 25 pixels on a side, with the peak pixel centered in the middle. We then calculate an accurate central position for the quasar in the image, and resample the image to produce a stamp image centered on the quasar. The size of the stamp image is also 25 × 25 pixels. Following Matsuoka et al. (2014), we assume that the central pixel (peak value) of the quasar image is completely dominated by the quasar/AGN component. Under this assumption, we scale the PSF and subtract it from the quasar image. The residual is referred to as the host galaxy component. Figure 8 demonstrates the procedure by showing three quasars.

From the above procedure, the fraction of the AGN (or host) component is simply calculated by doing aperture photometry on the PSF image and the quasar image. In our six quasars, the
host contribution is roughly between 19% and 37%. In order to measure the luminosity of an AGN at the rest-frame 5100 Å, we scale its spectrum in Figure 1 to match the mean of the i-band magnitudes obtained in IBRM. We then calculate the AGN luminosity from the spectrum after removing the host contribution. The absolute values of the AGN luminosities are listed in Table 2.

5.2. R–L Relation

The relation between the BLR size and quasar luminosity provides the basis for determining SMBH masses in high-redshift quasars/AGNs with single-epoch spectroscopy (for a recent review, see Shen 2013). Accurate measurements of SMBH masses are particularly important in the context of the co-evolution of the SMBH and host galaxy (Kormendy & Ho 2013). The masses from RM can be calibrated from the local $M_{\text{BH}}-\sigma_*$ relation (e.g., Ho & Kim 2015). Our sample is still small, and would not improve the R–L relation. On the other hand, the quasars in this sample are at relatively high redshifts, and thus may test the current R–L relation at $0.2 < z < 0.4$.

Figure 9 shows the current R–L relation from successful RM campaigns compiled by Bentz et al. (2013). Different emission lines have different ionization potentials, so the corresponding BLR sizes are different. The relation shown in Figure 9 was mostly built from H/$\beta$ measurements of local AGNs. We also plot the recent results on H/$\beta$ and Mg ii lags at $z \geq 0.3$ (the blue circles) from the SDSS-RM project (Shen et al. 2015c). Our results for the six quasars with lag detections are shown as the red circles. They are roughly consistent with the R–L relation derived from local AGNs. Our sample is primarily based on the H$\alpha$ line, which has a shallower ionization potential than H/$\beta$, and is thus expected to have a larger BLR size. However, the difference between the H$\alpha$ lag and H/$\beta$ lag is unclear, and may depend on quasar luminosity. Several previous studies show that the difference ranges between 20% and 50% (e.g., Kaspi et al. 2000; Kollatschny 2003; Bentz et al. 2010; Haas et al. 2011). Given the scatter in the relation, our lag measurements are still consistent with the previous results.

We note that our six quasars occupy a small part of the parameter space in Figure 9. This is due to the small sample size and the strong target selection bias. Our targets were selected to be bright, and they presumably have relatively large BLR sizes. If there were fainter quasars in our sample, we would not be able to detect their time lags (and thus they would not show up in Figure 9) because of the coarsely sample light curves. On the other hand, much more luminous quasars do not show up in the figure either, since these quasars have much longer time lags and cannot be detected in the IBRM duration, as we discussed in Section 4.3. Therefore, the consistency of our results with previous studies does not mean that we have validated the current R–L relation at $0.2 < z < 0.4$. A larger, unbiased sample covering a much larger parameter space is needed.

6. SUMMARY AND FUTURE PROSPECTS

We have presented our IBRM program, a photometric RM program with broad- and intermediate-band photometry. The intermediate bands that we chose are centered at 8045, 8505, and 9171 Å. They cover three wavelength ranges with relatively weak OH sky emission, thus imaging in these bands is very efficient. Our sample consists of 13 quasars at redshifts between 0.2 and 0.9. These quasars were selected to have strong H$\alpha$ or H/$\beta$ emission lines that are located in one of the intermediate bands. The IBRM campaign was carried out with the 90Prime camera on the Bok telescope. The 90Prime has a large FOV and covered 13 quasars within five pointings/fields. The five fields were observed in the i, z, and intermediate bands in 20–30 epochs. These epochs were unevenly distributed in a period of 5–6 months, so the cadence is not optimal for RM experiments. By using a large number of standard stars for each quasar, we achieved high accuracy on the photometric measurements. The combination of the broad- and intermediate-band photometry allows us to precisely determine the light curves of the optical continuum and emission line. We detected significant time lags between continuum and line emission in six (out of 13) quasars in our sample. The time lags are consistent with the R–L relation derived from H/$\beta$ in low-redshift AGNs.

Photometric RM with intermediate-band photometry has two major advantages. First, as with any implementation of photometric RM, it does not require spectroscopic observations, and can be easily performed with small telescopes. Second, the bandwidth of an intermediate filter is narrow enough that the line flux still contributes a significant fraction of the total flux in the band. Meanwhile, it is wider than narrow bands so that it is possible to include more than one target (at similar redshifts) per telescope pointing, which substantially increases observing efficiency.

Based on our experience from the IBRM program, we may increase our efficiency and improve our success rate in future RM campaigns with intermediate-band photometry. We plan to carry out a larger RM program using the Near-Earth Object Survey Telescope (NEOST) in Xuyi, China. NEOST is a 1 m telescope with a FOV of 9 deg$^2$. With such a large FOV, we can monitor several (up to ~10) quasars per telescope pointing. Our current IBRM experiment contains only 20–30 unevenly distributed epochs. We will make more observations (40–50
epochs) with better cadence, which will greatly increase the success rate and improve time-lag measurements. Ideally, we can complete this RM campaign for 100 quasars with 60 nights (45 epochs in 6 months) on the NEOST telescope.

We also plan to extend the baseline from 6 to 18 months, with more sparse sampling after 6 months. This is to explore higher-redshift and higher-luminosity quasars. The maximum redshift that the three intermediate bands can reach for Hβ is roughly 0.9, which is much higher than the redshifts of the majority of quasars shown in Figure 9. We will further extend this method to other lines such as Mg ii, although RM with Mg ii is significantly more difficult because the line is generally much weaker than Hα and Hβ.

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