Active Galactic Nuclei with Ultrafast Outflows Monitoring Project: The Broad-line Region of Mrk 79 as a Disk Wind

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Received 2019 June 3; revised 2019 November 5; accepted 2019 November 11; published 2019 December 16

Abstract

We developed a spectroscopic monitoring project to investigate the kinematics of the broad-line region (BLR) in active galactic nuclei (AGNs) with ultrafast outflows (UFOs). Mrk 79 is a radio-quiet AGN with UFOs and warm absorbers and has been monitored by three reverberation mapping (RM) campaigns, but its BLR kinematics are not yet understood. In this paper, we report the results from a new RM campaign of Mrk 79, which was undertaken with the Lijiang 2.4 m telescope. Mrk 79 appears to come out the faint state, with the mean flux approximately a magnitude fainter than the historical record. We successfully measured the lags of the broad emission lines including Hγ λ4861, Hβ λ4340, He II λ5876, and He I λ5876 with respect to the varying AGN continuum. Based on the broad Hβ λ4861 line, we measured a black hole mass of $M_\bullet = 5.13^{+1.57}_{-1.55} \times 10^7 M_\odot$, and an estimated accretion rate of $\dot{M}_\bullet = (0.05 \pm 0.02) L_{\text{Edd}} c^{-2}$, indicating that Mrk 79 is a sub-Eddington accretor. We found that Mrk 79 deviates from the canonical Radius–Luminosity relationship. The marginal blueshift of the broad He II λ5876 line detected from the rms spectrum indicates outflow of high-ionization gas. The velocity-resolved lag profiles of the broad Hγ λ4340, Hβ λ4861, and He I λ5876 lines show similar signatures such that the largest lag occurs in the red wing of the lines and then the lag decreases to both sides. These signatures may suggest that the BLR of Keplerian motion probably exists as outflow gas motion. All findings including UFOs, warm absorbers, and the kinematics of high- and low-ionization BLR, may provide indirect evidence that the BLR of Mrk 79 probably originates from a disk wind.

Unified Astronomy Thesaurus concepts: Seyfert galaxies (1447); Galactic winds (572); Galaxy accretion disks (562); Active galactic nuclei (16); Galaxy kinematics (602); Galaxy luminosities (603); Galaxy accretion (575); Supermassive black holes (1665)

Supporting material: machine-readable table

1. Introduction

In the past thirty years, reverberation mapping (RM; Bahcall et al. 1972; Blandford & McKee 1982) has been extensively adopted to investigate the kinematics of the broad-line region (BLR) of and to measure the mass of the accreting supermassive black hole (BH) in active galactic nuclei (AGNs). BH masses of ~100 AGNs have been measured by different RM campaigns (e.g., Peterson 1993; Peterson et al. 1998, 2004; Kaspi et al. 2000; Bentz et al. 2007, 2009b, 2010, 2013; Denney et al. 2009b, 2010; Barth et al. 2011a, 2011b; Peterson 2014; Du et al. 2015, 2018; Grier et al. 2017; De Rosa et al. 2018).

The canonical Radius–Luminosity relationship is constructed from these RM campaigns (Peterson et al. 1993; Wandel et al. 1999; Kaspi et al. 2000; Bentz et al. 2013), which provides an indirect way to estimate BH mass from a single spectrum. However, as the number of samples increases, this relationship becomes more scattered (~0.3 dex; Bentz et al. 2013; Grier et al. 2017; Du et al. 2018). It is possible to find the physics of this scatter by studying the long-term variation of the BLR with repeated RM campaigns (Peterson et al. 2002; Lu et al. 2016). The kinematic structures of the BLR for ~20 AGNs have been probed using velocity-resolved RM (e.g., Bentz et al. 2009b, 2010; Denney et al. 2009a, 2010; Barth et al. 2011a, 2011b; Grier et al. 2013; Du et al. 2016; Lu et al. 2016; Pei et al. 2017; De Rosa et al. 2018; Zhang et al. 2019). They usually include a virialized disk, inflow, and outflow (Bentz et al. 2009b; Grier et al. 2013), but the physical origins of the inflow and outflow remain unclear.
Mrk 79 is a nearby and radio-quiet (RQ) AGN (z = 0.022189 from NED) that has been monitored by three RM campaigns (Peterson et al. 1998). These campaigns successfully detected time delays of the broad Hβ line with respect to the continuum variation, but the kinematics of Mrk 79’s BLR is not yet understood. Therefore, Mrk 79 deserves to be monitored again to investigate the kinematics of the BLR, and to construct the Radius−Luminosity relationship of Mrk 79 (like the Radius−Luminosity relationship of NGC 5548; see Peterson et al. 2002; Lu et al. 2016; Pei et al. 2017; Kriss et al. 2019).

Second, based on the X-ray spectrum between 7 and 10 keV, ultrafast outflows (UFOs, i.e., highly ionized absorbers) have been detected in Mrk 79 through Fe XXV and Fe XXVI K-shell absorption lines with a blueshifted velocity $V_{\text{UFOs, out}} = (0.092 \pm 0.004)c$ (c is the speed of light, see Tombesi et al. 2010, 2011). Warm absorbers have also been detected in the soft X-ray spectrum, but the current energy resolution of the X-ray spectrum makes it hard to constrain its nature (Gallo et al. 2011; Tombesi et al. 2013). UFOs and warm absorbers are probably associated with an accretion disk wind in Mrk 79 because it is an RQ AGN (no jets; Tombesi et al. 2011). What is the connection between the BLR and the accretion disk wind?

On the one hand, a multiphase disk wind including hard X-ray absorbers (UFOs), soft X-ray absorbers (warm absorbers), and UV absorbers was confirmed in terms of the blueshift of X-ray and ultraviolet (UV) broad absorption lines (e.g., Murray & Chiang 1997; Leighly & Moore 2004; O’Brien et al. 2005; Tombesi et al. 2010, 2013; Hamann et al. 2018; Giustini & Proga 2019; Longinotti et al. 2019), in which these absorbers jointly or partially exist in AGNs (O’Brien et al. 2005; Tombesi et al. 2013). Therefore a disk wind model characterized by a multiphase stratified structure was developed to explain these phenomena (e.g., see Figure 5 of Tombesi et al. 2013, Figure 6 of Mas-Ribas 2019). In addition, outflows of the BLR are also found from UV and optical spectra. For example, (1) Richards et al. (2011) found that the blueshift of broad C IV emission lines are nearly ubiquitous, with a mean velocity of $\approx 810 \text{ km s}^{-1}$ for RQ AGNs; (2) in an RM study of spectroscopic monitoring, Hu et al. (2015) found that a blueshifted broad He II $\lambda 4686$ line is needed to reasonably decompose the optical spectrum; (3) based on the rest frame defined by the [O III] $\lambda 5007$ line, Ge et al. (2019) found the blueshift of the broad C IV emission line has a medium-strong positive correlation with the optical luminosity and the Eddington ratio. Murray et al. (1995) developed a model for line-driven wind from an accretion disk, which suggested that the absorbing gas cannot lie within the broad-line emitting region but can be cospatial with it or outside of it, and predicted that the high-ionization emission lines should be blueshifted relative to the low-ionization emission lines. Interestingly, the blueshift of absorbers and emitters jointly exist in a few AGNs (e.g., PDS 456). O’Brien et al. (2005) attributed this phenomenon to a decelerating, cooling outflow, which may be driven by radiation and/or magnetic fields, and suggested that the X-ray outflow could be the source of some of the BLR gas. In this case, the geometric and kinematic structures of the BLR could be modified by a decelerating, cooling outflow.

On the other hand, the signature of the outflowing BLR was just observed doubtlessly by velocity-resolved RM in Mrk 142 and NGC 3227 (Denney et al. 2009a, 2010; Du et al. 2016). It’s worth noting that these AGNs have different properties. Mrk 142 has very high accretion rates, and radiation pressure acting on the ionized gas may drive the outflow of the BLR (Du et al. 2015). However, NGC 3227 is a low-accretion AGN (Denney et al. 2010; Du et al. 2015), but studies have detected outflows of hard X-ray and soft X-ray absorbers with velocities of $\approx 2060 \text{ km s}^{-1}$ and $\approx 420 \text{ km s}^{-1}$ (i.e., UFOs and warm absorbers) from X-ray spectra (Markowitz et al. 2009). What drives the outflow of the BLR for AGNs with low accretion rates?

Motivated by the above questions, we will focus on investigating the BLR kinematics of AGNs with UFOs and explore potential connections between the BLR and UFOs (or an accretion disk wind). Therefore we developed an AGNs with UFOs monitoring project. This paper presents the results from the spectroscopic monitoring of Mrk 79. The paper is organized as follows. In Section 2, we describe the observations and the data reduction in detail. Data analysis and results including spectral measurement, time series analysis, the construction of velocity-resolved lag profiles, and estimates of the BH mass and so on are presented in Section 3. Section 4 is a discussion, and the summary is given in Section 5. We use a cosmology with $H_0 = 67 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_\Lambda = 0.68$, and $\Omega_M = 0.32$ (Planck Collaboration et al. 2014).

2. Observations and Data Reduction

2.1. Spectroscopic and Photometric Observations

The spectroscopic and photometric observations of Mrk 79 were taken using the Yunnan Faint Object Spectrograph and Camera (YFOSC) mounted on the Lijiang 2.4-m telescope (LJT), which is located at Lijiang Observatory and is administered by Yunnan Observatories of the Chinese Academy of Sciences (Fan et al. 2015; Wang et al. 2019). YFOSC is equipped with a back-illuminated $2048 \times 2048$ pixel CCD, with a pixel size of $13.5 \mu m$, a pixel scale of $0".283$ per pixel, and a $10'' \times 10''$ field of view. It is a versatile instrument for low-resolution spectroscopy and photometry (see Du et al. 2014; Lu et al. 2016).

The spectral monitoring of Mrk 79 started on 2017 November 1, and terminated on 2018 March 13. During the spectroscopic observations, we simultaneously observed a nearby comparison star along the slit as a reference standard, and used both LJT and Kaspi et al. (2000), and was recently adopted by Du et al. (2014, 2018), and Lu et al. (2016). In light of the average seeing of $\approx 1''3$ at the observatory site, we fixed the projected slit width to $2''5$. We used Grism 14, which provides a resolution of $92 \text{ Å mm}^{-1}$ (1.8 Å pixel$^{-1}$) and covers the wavelength range 3600−7460 Å. Standard neon and helium lamps were used for wavelength calibration. In total, we obtained 72 spectroscopic observations, spanning an observation period of 132 days. The median and mean cadences are 1.0 and 1.8 days, respectively. All spectra were obtained with a median air mass of 1.15, which means that atmospheric differential refraction has a negligible impact on our analysis (Filippenko 1982).

It should be noted that the standard spectral calibration method assumes that the [O III] $\lambda 5007$ flux is constant and uses it as an internal flux calibrator (e.g., Faushaugh 2017). To integrate put an extended [O III] $\lambda 5007$ emission region into a
spectroscopic slit, many previous RM campaigns adopted a broad slit (∼5″; see Table 12 of Bentz et al. 2013) at the cost of losing spectral resolution. In this case, the standard spectral calibration method using the [O III] λ5007 line as a calibrator provides precise internal flux calibration of the spectra (see Fausnaugh 2017). Actually, a relatively narrow slit increases the spectral resolution, and high spectral resolution is conducive to the following velocity-resolved time series analysis (Section 3.8). Therefore, we adopted a relatively narrow slit (2″/5) in spectroscopy. For a small spectrograph slit, using the [O III] λ5007 as an internal flux calibrator is not an optimal choice because the [O III] λ5007 emission regions of many AGNs (e.g., Peterson et al. 1995; Schmitt et al. 2003a, 2003b for NGC 4151) along with the host galaxy are (slightly or very) extended sources (see Appendix A), and varying observing conditions may cause an apparent variation in the flux of extended sources (for details, refer to Appendix A). While, in this case, a stable comparison star observed along with the object simultaneously in a narrow slit can provide for precise flux calibration of spectra (see Section 3.4 and Appendix A; Hu et al. 2015, as well).

The photometric images with the field of 10″ × 10″ were obtained using a Johnson V filter. In total, we obtained 62 photometric observations. Typically, two exposures of 90 s were taken for each individual observation.

2.2. Data Reduction

The photometric images were reduced following standard IRAF procedures using the IRAF (v2.16) package. The magnitude of the object (Mrk 79) and the comparison star were measured through a circular aperture with a radius of 5″/7, and differential magnitudes were obtained relative to four selected stars within the field of view. Figure 1 shows the light curve of the comparison star. The accuracy of the photometry is 1%, which demonstrates that the comparison star is stable enough to be used for flux calibration of the spectra. The photometric data of Mrk 79 will be used to check the spectral calibration in Section 3.4.

The two-dimensional spectroscopic data were reduced using the standard IRAF (v2.16) package. This process included bias subtraction, flat-field correction, wavelength calibration, and spectrum extraction. All spectra were extracted using a uniform aperture of 20 pixels (5″/7), and background was determined from two adjacent regions (+7″4 ∼ +14″ and −7″4 ∼ −14″) on both sides of the aperture region. Actually, a relatively small extraction aperture contributes to reducing the Poisson noise of the sky background and increasing the signal-to-noise ratio (S/N) of the spectrum. High S/N ratio is conducive to the following multicomponent decomposition of the spectrum (Section 3.2). The spectral flux of the target was calibrated by the comparison stars in two steps. (1) We produced the fiducial spectrum of the comparison star using data from nights with photometric conditions. (2) For each object/comparison star pair, we obtained a wavelength-dependent sensitivity function comparing the star’s spectrum to the fiducial spectrum. Then this sensitivity function was applied to calibrate the observed spectrum of the target (also see Appendix A; Du et al. 2014; Lu et al. 2016).

2.3. Data Processing

The flux-calibration spectra were corrected for Galactic extinction using the extinction map of Schlegel et al. (1998) at first. The variations of seeing and miscentering usually cause slight wavelength shifts and broadening of emission lines (Lu et al. 2016; Du et al. 2018). We corrected wavelength shifts using the [O III] λ5007 line as a wavelength reference, and corrected for broadening of emission lines by convolving the [O III] λ5007 line with its maximum width determined from 72 spectra. Then the spectra were transformed into the rest frame using the redshift (z = 0.022189). These processed spectra are adopted in the next analysis.

3. Data Analysis and Results

3.1. Mean and rms Spectra

The definition of a mean spectrum is (Peterson et al. 2004)

\[ F_\lambda = \frac{1}{N} \sum_{i=1}^{N} F_i(\lambda) \]  

and an rms spectrum is

\[ S_\lambda = \left\{ \frac{1}{N} \sum_{i=1}^{N} [F_i(\lambda) - \bar{F}(\lambda)]^2 \right\}^{1/2}, \]

where \(F_i(\lambda)\) is the \(i\)th spectrum and \(N\) is the total number of spectra obtained during the monitoring period. Using Equations (1) and (2), we calculated the mean and rms spectrum of Mrk 79 from the processed spectra and show them in Figure 2 (in blue). A zoom-in of the mean spectrum is inserted in Figure 2(a), and presents significant corona lines (such as [Fe VII] λλ5158, 5178, [Fe VII] λ5721, [Fe VII] λ6086, and [Ca VI] λ5310), narrow lines (e.g., He I λ4471, He I λ5876), and weak absorption-line features (e.g., see the red wing of He I λ5876 narrow line). [O III] emission lines should normally disappear in an rms spectrum because the flux of [O III] should not vary on the BLR reverberation timescale (Barth & Bentz 2016). However, Figure 2(b) shows that [O III] λλ4959, 5007 emission lines dramatically remain in the rms spectrum.

In practice, two scenarios will result in the [O III] emission remaining in the rms spectrum. (1) Residual [O III] emission is caused by the wavelength shift and broadening of the emission line. (2) As considered in Section 2.1 (the third paragraph), residual [O III] emission may be attributed to the apparent variation in the flux of [O III] caused by varying observing conditions because the narrow-line region (NLR) of Mrk 79 is slightly extended (Schmitt et al. 2003a, 2003b; Ho 2009; also see Appendix A). For the former, we have processed spectra of Mrk 79 strictly before calculating the rms spectrum, therefore the residuals of [O III] emission in the rms spectrum are not caused by the shift and broadening of emission lines. If the latter case holds, apparent variations in the flux of [O III] and of the host galaxy should have similar behavior (or be correlated).
Because the NLR and the host galaxy are extended sources. We will examine this in Section 3.4.

Based on the mean and rms spectra, we found that the broad He II λ4686 is very weak (see blue trace of Figure 2(a)), but its flux shows significant variation (see blue trace of Figure 2(b)) during the monitoring period. To determine the width of the broad He II λ4686 line from the rms spectrum, we ran 200 Monte Carlo simulations similar to the method adopted by Grier et al. (2012). We created 200 rms spectra from 200 randomly chosen subsets of the spectra, and obtained distributions of line width (FWHM) and positions of line core (C). The distributions give FWHM_{He II λ4686} = 9621 ± 812 km s^{-1} and C_{He II λ4686} = 4678.6 ± 3.9 Å. The latter corresponds to a blueshift of the broad He II λ4686 emission line with velocity of ∼450 km s^{-1}.

### 3.2. Spectral Fitting

To more accurately separate the broad emission features from each other, a spectral fitting scheme (SFS) is widely used in the spectroscopic measurements of AGN (e.g., Dong et al. 2008, 2011; Hu et al. 2008; Wang et al. 2009; Jin et al. 2012; Stern & Laor 2012; Liu et al. 2018; Lu et al. 2019). Especially in RM studies, SFS has proven necessary to measure the light curves when broad emission lines are highly blended with each other (Bian et al. 2010; Barth et al. 2013, 2015; Hu et al. 2015). Beyond that, by modeling and removing the contamination of a strong host galaxy which varies from night to night due to seeing and guiding variations, SFS can improve the measurement quality of light curves of the continuum and broad emission lines (Hu et al. 2015, 2016).

In order to decompose the spectra of Mrk 79 using SFS, we followed a previous method described by Hu et al. (2015) with some changes described below. The fitting was performed in the rest wavelength range 4180–6115 Å, which has no second-order effect (secondary spectrum) in our analysis because its contamination occurs at wavelengths longer than 6250 Å. The fitting components include: (1) a single power law (f_b ∝ λ^α, α is the spectral index) for the AGN continuum. In practice, a single power law is successfully used to fit AGN continua over a broad region (∼4150–6200 Å; Hu et al. 2015); (2) the starlight from the host galaxy modeled by a template with age 11 Gyr and metallicity Z = 0.05 from Bruzual & Charlot (2003); (3) Fe II multiplets modeled by an Fe II template from Boroson & Green (1992) convolved with a Gaussian function; (4) four single Gaussians for the broad emission lines including Hβ λ4861, Hγ λ4340, He II λ4686, and He I λ5876, respectively; (5) three double Gaussians for the [O III] doublets λ5007/λ4959 and Hβ λ4861 narrow line; (6) a set of several single Gaussians with the same velocity width and shift for narrow emission lines including Hα λ4340, [O III] λ4363, He I λ4471, He II λ4686, He I λ5876, [N I] λ5200, and several coronal lines (Figure 3). Following Hu et al. (2015), we fitted the above models simultaneously to the spectra of Mrk 79 in the fitting region. The processed spectra (see Section 2.3) were fitted in two steps. We fitted the mean spectrum at first (Figure 3). During the fitting, the flux ratio of [O III] doublets was fixed to the theoretical value of 3. The shift and line width of the broad He II λ4686 emission line were fixed to the best value measured in Section 2.3 because it is too weak to restrict the model. The rest of the model parameters were allowed to vary. Then in the fitting of individual spectra (Figure 3), we fixed the spectral index and the flux ratios of the narrow emission lines relative to [O III] λ5007 to the corresponding values given by the best fit of the mean spectra. The spectra of Mrk 79 show weak features of Fe II multiplets, so we also fixed their width to the value fitted in the mean spectrum. In practice, this operation is reasonable since we have corrected for the broadening of emission lines (see Section 2.3).

Using the fitting results, we calculated the revised mean and rms spectra after subtracting the narrow emission lines, and plotted them along with the original mean and rms spectra in Figure 2. Comparing the revised mean spectrum (in red) with the original mean spectrum (in blue), we found that the narrow emission lines are well fitted and subtracted. From Figure 2(b), we found that the residuals of [O III] λ4958, 5007 almost disappear in the revised rms spectrum, and minor residuals are comparable with mean errors (dashed green line).

### 3.3. Host Galaxy

Mrk 79 was observed by the Hubble Space Telescope (HST) Advanced Camera for Surveys/High resolution channel (ACS/HRC) with the F555M filter. Two-dimensional surface brightness decomposition of Mrk 79 was performed by Bentz et al. (2009a) and Kim et al. (2017) using the code GALFIT (Peng et al. 2002; Kim et al. 2008). Kim et al. (2017) recently analyzed high-resolution HST images of 235 low-redshift Type 1 AGNs to study the structures of the host galaxies. We adopted the best-fit model for the host galaxy of Mrk 79 from Kim et al. (2017), which is shown in Figure 4. Bentz et al. (2009a) also
analyzed HST images of 35 RM AGNs to measure the contribution of host light to the total luminosity at 5100 Å. They concluded that the flux of host light at 5100 Å for Mrk 79 is 

$$F_{\text{host}}[1 + z] = 1.42 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}$$

within an aperture of $5''0 \times 7''6$ (Ap; lime rectangle). In this work, the extraction aperture of the spectrum is $2''5 \times 5''7$ with position angle $-99^\circ$ (Al; red rectangle in Figure 4). Integrating the photons in the extraction apertures of $2''5 \times 5''7$ and $5''0 \times 7''6$, respectively, we obtained the ratio of total photons of the host galaxy in two apertures $A_L/A_P = 0.60$. Using this ratio and the host-galaxy flux $1.42 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}$, we estimated the host-galaxy flux in our adopted extraction aperture for Mrk 79, which yields $F_{\text{host,Ap}}[1 + z] = 0.85 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}$. The fitting of mean spectrum yields an average host-galaxy flux of $F_{\text{host}}[1 + z] = (0.80 \pm 0.09) \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}$, where the uncertainty 0.09 is the standard deviation estimated from the fitted host-galaxy components (Section 3.2). This flux is consistent with the above estimate from the HST image because measuring the flux contribution from the image has an uncertainty of $\sim 10\%$ (Bentz et al. 2013). This consistency indirectly shows that the spectral decomposition of Mrk 79 is robust and the host galaxy of Mrk 79 is well fit with a bulge, a bar, and a disk (see Kim et al. 2017).

3.4. Light Curves

The light curves of AGN continuum at 5100 Å ($F_{\text{AGN}}$) and broad emission lines ($F_{\text{H}/\beta}, F_{\text{He I}4686}$, and $F_{\text{He II}5876}$) were generated from the best-fit model (the featureless power law and the broad-line components). Table 1 provides the data of these light curves along with the photometric light curve of Mrk 79. We also measured the fluxes of the host galaxy ($F_{\text{gal}}$) and [O III] $\lambda 5007$ ($F_{\text{[O III]}}$) from the best-fit model, and directly measured the light curve of continuum at 5100 Å ($F_{5100, \text{obs}}$, which is contaminated by the host galaxy) from the above processed spectra (see Section 2.3). We calculated the variability amplitude of the light curve by (see Rodriguez-Pascual et al. 1997)

$$F_{\text{var}} = \frac{(\sigma^2 + \Delta^2)^{1/2}}{\langle F \rangle}$$

and its uncertainty (Edelson et al. 2002)

$$\sigma_{\text{var}} = \frac{1}{F_{\text{var}}} \left( \frac{1}{2N} \right)^{1/2} \sigma^2,$$

where $\langle F \rangle = N^{-1} \sum_{i=1}^{N} F_i$ is the average flux, $F_i$ is the flux of the $i$th observation of the light curve, $N$ is the total
number of observations, $\sigma^2 = \sum_{i=1}^{N}(F_i - \langle F \rangle)^2/(N - 1)$, $\Delta^2 = \sum_{i=1}^{N} \Delta_i^2/N$, and $\Delta_i$ is the uncertainty of $F_i$. Table 2 lists the statistics of the light curve.

We compared the light curves of $F_{\text{AGN}}$ and $F_{\text{SS100,obs}}$ (Figures 5(a) and (b)), and found that the light curve of $F_{\text{AGN}}$ has a larger variability amplitude ($F_{\text{var}}\% = 9.61$) than the light curve of $F_{\text{SS100,obs}}$ ($F_{\text{var}}\% = 6.26$). This shows that the light curve of $F_{\text{AGN}}$ has improved after removing the contamination of the host galaxy. Both light curves measured from the spectra are consistent with the photometric light curve of Mrk 79 (Figure 5(c)). This consistency shows that the stable comparison star can provide precise flux calibration of spectra.

We checked the fluxes of the host galaxy and the [O III] $\lambda$5007 emission (measured from the best-fit components) in Figures 11(a) and (b), and found that both the fluxes have similar apparent variation in the time domain, and also that the host-galaxy fluxes (11%) are more scattered than that of [O III] $\lambda$5007 (5%). Similar phenomena are found in Mrk 382 by Hu et al. (2015). These measurement results are consistent with the considerations of spectroscopic observation in Section 2.1 (the third paragraph). That is, monitoring the spectra of Mrk 79 in a relatively narrow slit ($2''5$) increases the spectral resolution, but varying observing conditions cause apparent variations in flux of the slightly extended components observed in the narrow slit (including the [O III] emission region and the host galaxy). The apparent variation in flux of the [O III] $\lambda$5007 leads to [O III] remaining in the rms spectrum, which supports the second scenario mentioned in Section 3.1.

In order to qualitatively study the apparent variation in flux of the host galaxy and the [O III] $\lambda$5007 emission, we have insight into the details of the spectroscopy and flux calibration in Appendix A. Briefly, seeing is a major factor in responding to varying observing conditions, which could change from one exposure to the next. If two point sources (the comparison star and AGN) are kept in a line parallel to the narrow slit ($2''5$), the fractions of light loss due to varying seeing are identical (Figure 10), that is the stable comparison star can provide precise flux calibration of spectra (see Figure 5 and accompanying statements). However, for slightly or very extended components in the same slit, the fractions of light loss due to varying seeing are less than for the point source (Figure 10 in Appendix A). In practice, the above analysis is consistent with seeing-induced aperture effects addressed by Peterson et al. (1995). Consequently, the calibrated fluxes of the slightly extended components should correlate with varying seeing. The host-galaxy fluxes should be more scattered than the [O III] region’s fluxes with varying seeing, because the intrinsic size of the host galaxy is larger than the [O III] emission region. The elaborate analysis is provided in Appendix A. Ultimately, our measurement results in fluxes of the slightly extended components (i.e., Figures 11 and 12) from the spectral fitting productions are consistent with the above analysis (for details, refer to Appendix A); this consistency demonstrates that the SFS performs correct decomposition of multicomponents.

### 3.5. Optical Luminosity

Using the light curve of AGN continuum at 5100 Å generated from the best-fit power law, we obtained the mean flux of $F_{\text{AGN}}[1 + z] = (2.33 \pm 0.23) \times 10^{-15} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1}$, which corresponds to the monochromatic luminosity of $L_{\lambda_{5100}} = (1.45 \pm 0.14) \times 10^{43} \text{erg s}^{-1}$ in the present epoch. Before this RM campaign, three-season RM campaigns for Mrk 79 were finished by Peterson et al. (1998), and the data were updated and published in a series of works (e.g., Peterson et al. 2004; Zu et al. 2011; Bentz et al. 2013). Primary parameters along with values are summarized in Table 3, where the values of H$\beta$ lags quoted in Table 3 are compiled from latest result of Bentz et al. (2013). Comparing these fluxes ($F_{\text{AGN}}[1 + z]$) for the host galaxy correction, we found that Mrk 79 appears to come out the faint state during the monitoring period. The
mean flux is approximately a magnitude fainter than the previous record holder. We checked the historical data (Peterson et al. 1998), and found that the highest luminosity state of Mrk 79 appeared at JD ∼ 2448.400 days. Similar to the famous NGC 5548 (Lu et al. 2016), the huge variation of AGN continuum allows us to (1) investigate the variation of the BLR similar to NGC 5548 (Lu et al. 2016); and (2) construct the Radius–Luminosity relationship of Mrk 79, similar to the $R_{\text{BLR}} - L_{5100}$ relationship of NGC 5548 (Lu et al. 2016; Pei et al. 2017).

**Figure 6.** Light curves and the results of cross-correlation analysis. The left panels (a)–(e) are the light curves of AGN continuum at 5100 Å and the broad emission lines calculated from the best-fit component. The right panels (aa)–(ea) correspond to the ACF of continuum and the CCF between the light curves of broad emission lines (b)–(c) and the continuum variation (a), respectively. We noted the variability amplitude $F_{\text{var}}$% in the light curve panels, and noted the maximum cross-correlation coefficient ($r_{\text{max}}$) in CCF panels. The units of $F_{\text{AGN}}$ and emission lines (including Helium and Balmer) are erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ and erg s$^{-1}$ cm$^{-2}$, respectively.

**Table 2**

Statistics of the Light Curve for Mrk 79 in this Campaign

| Time Series | $F_{\text{continuum}}[1 + z]$ | $F_{\text{AGN}}[1 + z]$ | $F_{\text{H}}[1 + z]$ | $F_{\text{He}}[1 + z]$ | $F_{16}[1 + z]$ | $F_{16}[1 + z]$ |
|-------------|-------------------------------|-------------------------|----------------------|----------------------|----------------|----------------|
| Mean Flux   | 3.22 ± 0.21                   | 2.33 ± 0.23             | 1.00 ± 0.10          | 2.63 ± 1.21          | 2.61 ± 0.14   | 4.64 ± 0.42   |
| $F_{\text{var}}$ (%) | 6.26 ± 0.57                   | 9.61 ± 0.88             | 8.53 ± 0.92          | 45.37 ± 4.06         | 5.33 ± 0.48   | 8.28 ± 0.85   |

Note. The mean flux $F_{\text{continuum}}[1 + z]$ in units of $10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$, the mean flux of other time series have the same units as in Table 1.
3.6. Line Profile Measurements

The broad emission lines in our spectral fitting window. Hence, we measured the velocity widths of these broad emission lines from the best-fit model. Using Equations (1) and (2), we obtained the mean and rms spectra of these broad lines at first. Their velocity widths (FWHM & $\sigma_{\text{line}}$) are used as the optimum values. As adopted in Section 3.1, to estimate the corresponding errors, we generated 200 mean and rms spectra (realizations) from 200 randomly chosen subsets of the spectra, and measured all velocity widths from simulated realizations. Then we used the standard deviations as errors of the optimum values. Whitte (1992) obtained an [O III] $\lambda$5007 width FWHM = 350 km s$^{-1}$ of Mrk 79 from a high-resolution spectrum. Comparing this width to those from our spectra (FWHM = 900 km s$^{-1}$), we obtained a broadening of 829 km s$^{-1}$. After correcting the broadening, we listed the widths of the broad lines in Table 4. In spectral fitting, the velocity width of broad He II $\lambda$4686 line was fixed to the value estimated from the rms spectrum (see Section 3.1), therefore we only give its velocity width from the rms spectrum in Table 4.

3.7. Lags of the Broad Emission Lines

We measured the reverberation lags of the broad emission lines (H$\gamma$ $\lambda$4340, H$\beta$ $\lambda$4861, and H e I $\lambda$5876) with respect to the continuum variation ($F_{\text{AGN}}$), using the standard interplanetary cross-correlation function (ICCF) method (Gaskell & Sparke 1986; Gaskell & Peterson 1987; White & Peterson 1994; see Figure 6). The reverberation lags are usually measured from peak ($\tau_{\text{peak}}$) and centroid ($\tau_{\text{cent}}$) of the ICCF, where $\tau_{\text{peak}}$ corresponds to the maximum correlation coefficient $r_{\text{max}}$, and $\tau_{\text{cent}}$ is measured around the peak above a typical value ($r \geq 0.8 r_{\text{max}}$). The uncertainties of $\tau_{\text{peak}}$ and $\tau_{\text{cent}}$ were obtained using the Monte Carlo “flux randomization and random subset sampling” method described by Peterson et al. (1998, 2004). The Monte Carlo simulations were run with 5000 realizations, and the cross-correlation peak and centroid distribution (CCPD and CCCD) were created from the generated samples. The uncertainties of $\tau_{\text{peak}}$ and $\tau_{\text{cent}}$ were then calculated from the CCPD and CCCD, respectively, with a 68.3% confidence level (1$\sigma$).

Table 4 lists the lags of the broad emission lines including $\tau_{\text{cent}}$, $\tau_{\text{peak}}$, and the maximum cross-correlation coefficients ($r_{\text{max}}$). In the low luminosity state of Mrk 79 (see Section 3.5), the lag of H$\beta$ $\lambda$4861 relative to the continuum variation is significantly shorter than the results of early RM campaigns (see Table 3). This is similar to the finding in the better observed NGC 5548 that the BLR size shortens with decreasing luminosity (e.g., Peterson et al. 1999, 2002; Bentz et al. 2007; Lu et al. 2016; De Rosa et al. 2018; Krisi et al. 2019). In addition, the lag of He II $\lambda$4686 relative to the continuum variation approximates zero, which is consistent with other objects (e.g., Mrk 1511, see Barth et al. 2013).

3.8. Velocity-resolved RM

The BLR is an extended region and the velocity of the gas is most likely a function of radius. The BLR gas in different radii should respond to the continuum variations with slightly different delays. The reverberation lags measured between the continuum variations and the total fluxes of the broad emission lines in Table 4 represent the radii averaged by the emissivity function of the BLR. Based on a single broad emission line, velocity-resolved RM was widely used to reveal the kinematic signatures of the BLR in many AGNs (e.g., Bentz et al. 2009b, 2010; Denney et al. 2009a, 2010; Barth et al. 2011a, 2011b; Grier et al. 2013; Du et al. 2016; Lu et al. 2016; Pei et al. 2017; De Rosa et al. 2018; Zhang et al. 2019). Although three RM campaigns of Mrk 79 were performed before the present campaign, the study of the BLR kinematics is still blank. In this section, we construct the velocity-resolved lag profiles of the broad emission lines (H$\beta$ $\lambda$4861, H$\gamma$ $\lambda$4340, He II $\lambda$4686, and He e I $\lambda$5876). Following previous methods...
were determined using the same procedures as described in
reverberation lag of each bin and the associated uncertainty
(11 The instrumental broadening
where
is the gas kinematics of the BLR during the monitoring period.

Bin6
i.e., Bin 1–9 from blue wing, line core to red wing of broad lines). Using Equation (3), we calculated variability amplitudes \( F_{\text{var}} \) of the velocity-resolved light curves and note these values in the left panels of Figures 13–16. The reverberation lag of each bin and the associated uncertainty were determined using the same procedures as described in Section 3.7. The results of cross-correlation analysis are shown in the right panels of Figures 13–16.

Bottom panels of Figure 7 show the velocity-resolved lag profiles (VLPs) of the broad H\( \beta \) \( \lambda 4861 \), H\( \gamma \) \( \lambda 4340 \), He II \( \lambda 4686 \), and He I \( \lambda 5876 \) emission lines. The vertical dashed lines are the edges of the velocity bins. Each bin is labeled with the \text{Bin} number, which is a one-to-one correspondence with Figures 13–16. For the VLP of He II \( \lambda 4686 \), the absolute value of 9 velocity-dependent delays are less than 0.5 day, which is shorter than median sampling of 1.0 day. A higher sampling is necessary to construct a clear VLP of the broad He II \( \lambda 4686 \) line by decreasing the errors. The VLPs of H\( \gamma \) \( \lambda 4340 \), H\( \beta \) \( \lambda 4861 \), and He I \( \lambda 5876 \) almost have the same kinematic signatures. They demonstrate that the high-velocity gas in the wings exhibits a shorter lag than the low-velocity gas. This is consistent with the virial nature of gas motion in the BLR (Bentz et al. 2009b; Grier et al. 2013), that is the gas kinematics of the BLR during the monitoring period is dominated by Keplerian gas motion. However, the lag in the red wing is slightly larger than the lag in the blue wing, and the largest delay response occurs in the red side of the line core (i.e., \text{Bin} \#; \sim \pm 1500 \text{ km s}^{-1} \) for these broad emission lines. A similar signature has been seen in NGC 3227 (see Figure 3 of Denney et al. 2009a). This is a signature of outflow gas motion (Bentz et al. 2009b; Grier et al. 2013). These complicated signatures should suggest that the BLR of Keplerian motion in Mrk 79 probably exists as the outflow gas motion during the monitoring period.

3.9. BH Mass and Accretion Rates

Using the RM measurements of the broad emission lines, we determined BH mass of Mrk 79 by the equation

\[
M_\bullet = f_{\text{BLR}} \frac{c^2 t_{\text{BLR}} V_{\text{BLR}}^2}{G} = f_{\text{BLR}} \text{VP},
\]

where \( c^2 t_{\text{BLR}} \) is the size of the BLR, \( c \) is the speed of light, \( t_{\text{BLR}} \) is the lag of the broad emission line with respect to the continuum variation, \( G \) is the gravitational constant, \( V_{\text{BLR}} \) (i.e., FWHM or \( \sigma_{\text{line}} \)) is the velocity width of the broad emission lines, and VP is commonly called the virial product. The coefficient \( f_{\text{BLR}} \), called the virial factor, depends on the geometry, kinematics, and inclination of the BLR.

We first calculated VP based on the different broad emission lines and tabulated results are in Table 4. Graham et al. (2011) was the first to evaluate the virial factor \( f_{\text{BLR}} \) taking into account the morphology of the host galaxies, and found that the factor \( f_{\text{BLR}} \) for barred galaxies is three times lower than that for nonbarred galaxies. Ho & Kim (2014) reevaluated the factor \( f_{\text{BLR}} \) for the RM AGN sample taking into account the bulge type and found that the systematic difference in \( f_{\text{BLR}} \) between barred and nonbarred galaxies qualitatively resembles the dependence on bulge type. Ho & Kim (2014) suggested that pseudobulge notably has a lower \( f_{\text{BLR}} \) than the classical bulge. For FWHM measured from the mean spectrum, \( f_{\text{BLR}} = 0.5 \pm 0.2 \) for pseudobulges, whereas \( f_{\text{BLR}} = 1.3 \pm 0.4 \) for classical bulges. For \( \sigma_{\text{line}} \) measured from the rms spectrum, \( f_{\text{BLR}} = 3.2 \pm 0.7 \) for pseudobulges, whereas \( f_{\text{BLR}} = 6.3 \pm 1.5 \) for classical bulges. The host galaxy of Mrk 79 has a classical bulge (Kim et al. 2017). Based on the broad H\( \beta \) line, multiplying virial factors \( f_{\text{BLR}} = 1.3 \pm 0.4 \) and \( f_{\text{BLR}} = 6.3 \pm 1.5 \) to \( \text{VP}_{\text{FWHM}}(=2.9\times10^{15}M_\odot) \) and \( \text{VP} \) \( \pm (=0.8\times10^{15}M_\odot) \), we obtained \( M_\bullet = 3.79^{+1.36}_{-1.35} \times10^6 M_\odot \) and \( 5.13_{-1.55}^{+1.57} \times10^6 M_\odot \), respectively. Our measurement of BH mass for Mrk 79 is consistent with previous results (see Peterson et al. 1998; Bentz et al. 2013). The bulge of Mrk 79 has a stellar velocity dispersion of \( (130 \pm 12) \text{ km s}^{-1} \) (Nelson et al. 2004). Using the latest \( M_\bullet - \sigma_\text{bulge} \) relation (Kormendy & Ho 2013), we obtained \( M_\bullet (\sigma_i = 4.68 \times 10^6 M_\odot) \) with a scatter of 0.34 dex, which is consistent with estimates from \( \text{VP} \) \( \pm \) and \( \text{VP}_{\text{FWHM}} \).

Based on the standard model of an accretion disk, the dimensionless accretion rates are related to the 5100 \( \AA \) luminosity and BH mass via (Du et al. 2015)

\[
\dot{m} = \frac{M_\bullet}{L_{\text{Edd}}} = 20.1 \left( \frac{\ell_{44}}{\cos i} \right)^{3/2} \epsilon_0^{-2},
\]

where \( M_\bullet \) is the mass accretion rate, \( L_{\text{Edd}} \) is the Eddington luminosity, \( c \) is the speed of light, \( \ell_{44} = L_{5100}/10^{44} \text{ erg s}^{-1} \) is optical luminosity at 5100 \( \AA \), \( M_\bullet = M_\odot/10^5 M_\odot \) is BH mass, and \( \cos i \) is the cosine of the inclination of the accretion disk. Inclination \( i = 24^\circ \) for Mrk 79 (Gallo et al. 2011). Using \( M_\bullet = 5.13_{-1.55}^{+1.57} \times 10^6 M_\odot \) and \( L_{5100} = (1.45 \pm 0.14) \times 10^{43} \text{ erg s}^{-1} \), we obtained accretion rates \( \dot{m} = (0.05 \pm 0.02) L_{\text{Edd}}^{-2} \), indicating that Mrk 79 is a sub-Eddington accreting AGN.

4. Discussion

4.1. Indirect Evidence of the BLR as a Disk Wind

On the one hand, UFPs and warm absorbers are identified in terms of the X-ray spectrum for Mrk 79 (Tombesi et al. 2010, 2011; Gallo et al. 2011), but their geometries remain unclear (Parker et al. 2018). We do not know whether blueshifted UV absorbers/emitters exist in Mrk 79 in absence a UV spectrum. In Section 3.1, we detected a marginal blueshift of the broad He II \( \lambda 4686 \) line with a velocity of \( \sim 450 \text{ km s}^{-1} \), which indicates an outflow of high-ionization gas (e.g., He II emitters). But it is significantly slower than the velocity of UFPs (0.016 \( \text{V}_{\text{FWHM(out)}} \)). As suggested by a disk wind model (Murray et al. 1995; O’Brien et al. 2005; Tombesi et al. 2013), this result may indicate that the X-ray outflow could be the source of some of the BLR gas. In addition, based

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11 The instrumental broadening \( \sigma \) is \( 829 \text{ km s}^{-1} \) for a \( 2''/5 \) slit. The average broadening in each velocity bin is significantly smaller than the bin width \( (~1300 \text{ km s}^{-1}) \), which means that the instrumental broadening has a negligible impact on our analysis.
on the velocity-resolved lag profiles of broad He I $\lambda$5876, H$\beta$ $\lambda$4861, and H$\gamma$ $\lambda$4340 lines (Section 3.8), we found that low-ionization gas of the BLR exhibits the outflowing signature during the monitoring period. Meanwhile, we found that Mrk 79 is similar to NGC 3227 (see Section 1) in some aspects. For example, (1) UFOs and warm absorbers were detected in both AGNs; and (2) the low-ionization BLR of both AGNs exhibits the outflowing component (see Section 3.8 and Denney et al. 2010). Based on velocity-resolved RM, we do not find without a doubt that the BLR exhibits an outflowing component expected for a normal AGN (i.e., no disk wind) so far. These findings may indicate that the outflowing BLR could

Figure 7. The rms profiles (top panels) and velocity-resolved lag profiles (bottom panels) of the broad H$\gamma$, H$\beta$, He I, and He II lines. The vertical dashed lines are the edges of the velocity bins. Each bin is labeled with Bin number (Bin 1–9), which is a one-to-one correspondence with Figures 13–16.
be associated with a disk wind, and may support the notion that a disk wind could be the source of some of the BLR gas as suggested by O’Brien et al. (2005). All of these phenomena including UFOs, warm absorbers, and the kinematics of the high- and low-ionization BLR, may provide indirect evidence that the BLR of Mrk 79 probably originates from a disk wind. However, simultaneous observations of multiband spectra are necessary to further constrain this speculation.

It should be noted that for NGC 3227, one of the candidate AGNs with UFOs, the outflowing BLR in 2007 (Denney et al. 2010) turned to a virialized BLR in 2012. De Rosa et al. (2018) suggested that the most likely reason for this change is that the BLR structure is probably complex and consists of multiple components—a disk and a wind. In this case, the decelerating and cooling outflow may gradually fall and turn to virialization, or it could be that the BLR kinematics are intrinsically variable on the dynamical timescale as we saw in NGC 5548 (Lu et al. 2016; De Rosa et al. 2018; Xiao et al. 2018; Kriss et al. 2019). Therefore, the different BLR kinematics will be observed from the different campaigns.

On the other hand, when NGC 5548 appeared to come out of faint state (e.g., Pei et al. 2017; De Rosa et al. 2018; Kriss et al. 2019), the broad emission lines failed to respond to variations in the continuum flux as the BLR “holiday.” Dehghanian et al. (2019) argued that X-ray absorption (observed by Mehdipour et al. 2016), produced by a transient obscurer, was present throughout the BLR “holiday” of NGC 5548. Based on X-ray and UV band monitoring of NGC 5548, Kriss et al. (2019) combined observational facts including the obscurer and the departure of NGC 5548’s BLR from the radius–luminosity relationship (Peterson et al. 2002; Pei et al. 2017; De Rosa et al. 2018), and suggested that the obscurer is a manifestation of a disk wind launched in the brightening state. Coincidentally, what has been happening in better-studied NGC 5548 seems to have been happening in Mrk 79 as well. Both appear to come out of faint states, the Hβ lags are too short for the low-luminosity state, and both are suspected of triggering disk winds. Unfortunately, we do not have UV or X-ray spectra of Mrk 79.

It is worth noting that outflows of RQ AGN should be jointly triggered and controlled by central gravity and magnetic or (and) radiation pressure. In this case, the velocity of outflows should anticorrelate with BH mass, and positively correlate with magnetic or (and) radiation pressure. We compiled blueshifted velocities of the broad He II λ4686 emission line from Hu et al. (2015) and this work, and investigated the relationship between the blueshifted velocity of He II λ4686 emitters and AGN properties including BH mass, luminosity of broad Hβ line (which is used as proxy of UV luminosity), and accretion rates in Figure 8. It should be noted that, in this small sample, a disk wind was only been detected in Mrk 79 and Mrk 1044 (Parker et al. 2018). This sample shows a possible trend that the blueshifted velocity of He II emitters are anticorrelated with BH mass, which may suggest that central gravity plays a potential role in the terminal velocity of the outflow. We cannot see a clear trend between the blueshifted velocity of He II emitters and the rest of the AGN properties (Figures 8(b) and (c)). A larger sample is necessary to responsibly investigate these relations. On the other hand, based on the results of 18 RM campaigns of NGC 5548, Lu et al. (2016) recently found that the BLR size (rBLR) follows the variation of optical luminosity on the long-term timescale for NGC 5548 but with a time delay of ∼3 yr (also see Kriss et al. 2019), and implies the potential role of radiation pressure. Mrk 79 has been monitored by four RM campaigns so far (including this work); nevertheless, more and dense RM campaigns are necessary to investigate this nature.

In addition, many possible origins of the BLR have been developed besides the above case. For example, a series of works suggested that part of the BLR gas (or broad emission line) originates from the outer region of the accretion disk (e.g., Collin-Souffrin 1987; Collin-Souffrin & Dumont 1990), but this scenario only produces low-ionization emission lines; Wang et al. (2017) modeled Hβ profiles using a dynamical model of different types of clouds and suggested that tidally disrupted clumps from the torus may represent the source of the BLR; Czerny & Hryniewicz (2011) suggested that the BLR is a failed dusty wind from the outer accretion disk (also see Czerny et al. 2017); Baskin & Laor (2018) suggested the BLR originates from the dusty inflated accretion disk (see Figure 13 of Baskin & Laor 2018). However, whether these possible origins of the BLR are an intermediate state (phase) of a multiphase disk wind should be studied in the future.

Figure 8. Relation between blueshift velocity of the broad He II λ4686 line and AGN properties including BH mass, luminosity of the broad Hβ line, and accretion rates. A disk wind was just detected in Mrk 79 and Mrk 1044; they are connected by a dashed line.
4.2. Radius–Luminosity Relation

Many works focused on investigating the kinematics of the BLR in NGC 5548, and constructed its $R_{\text{BLR}} - L_{5100}$ relationship (Peterson et al. 2004; Bentz et al. 2007; Denney et al. 2010; Lu et al. 2016; Pei et al. 2017; De Rosa et al. 2018). Comparing the observational features of Mrk 79 in past RM campaigns (see Section 3) with NGC 5548, we seemingly saw another “NGC 5548–like” AGN in some aspects. For example, (1) the velocity widths of broad emission lines (such as Hβ) are very broad ($>4000$ km s$^{-1}$), as if from a broad-line Seyfert galaxy; (2) they have a classical bulge in the host galaxy (Kim et al. 2017); (3) their BLR size and optical luminosity exhibit large variation (see Table 3; Lu et al. 2016; Kriss et al. 2019). Mrk 79 is a new candidate that can be used to construct another $R_{\text{BLR}} - L_{5100}$ relationship for an individual object because of the enormous change in the AGN continuum and the BLR size (Table 3). Figure 9 presents the canonical $R_{\text{BLR}} - L_{5100}$ relationship (slope = 0.53) from Bentz et al. (2013) along with the $R_{\text{BLR}} - L_{5100}$ relationship of NGC 5548 (slope = 0.86, Lu et al. 2016). Black dots with error bars display the $R_{\text{BLR}} - L_{5100}$ relationship of the NGC 5548 reverberations, red circles with error bars display the $R_{\text{BLR}} - L_{5100}$ relationship of Mrk 79 reverberations. We found that the current $R_{\text{BLR}} - L_{5100}$ relationship of Mrk 79 deviates from the canonical $R_{\text{BLR}} - L_{5100}$ relationship (blue line) and NGC 5548’s $R_{\text{BLR}} - L_{5100}$ relationship (black line).

We note that previous works have described how the BLR radius in an individual object changes as the mean optical luminosity varies with time (e.g., Baldwin et al. 1995; Peterson et al. 1999, 2002). Based on NGC5548’s results from 13 seasons of RM campaigns, Peterson et al. (2002) found that the observed relation between the BLR radius and the luminosity in an individual AGN (Figure 5 of Peterson et al. 1999 and Figure 3 of Peterson et al. 2002) is consistent with the prediction of a simple photoionization equilibrium model. However, the latest studies have found that (1) the BLR radius correlates with the averaged luminosity of the AGN but with a delay, and this delay coincides with the BLR’s dynamical timescale (Ulrich et al. 1991; Lu et al. 2016; Kriss et al. 2019); and (2) the shortened Hβ lags correlate with the accretion rates of AGN (e.g., Du et al. 2018). These results may imply that the BLR physics are probably complicated, and the evolution of the BLR structure and kinematics may change the correlation between the BLR radius and the luminosity of the AGN predicted by a photoionization equilibrium model. It is possible that comparing the $R_{\text{BLR}} - L_{5100}$ relationships of different AGNs (e.g., NGC 5548, Mrk 79, and so on) in the near future and investigating their similarities and differences could help us to understand the scatter ($\sim 0.3$ dex, see Bentz et al. 2013; Grier et al. 2017; Du et al. 2018) of the canonical $R_{\text{BLR}} - L_{5100}$ relationship.

5. Summary

We developed a monitoring project to investigate the kinematics of the BLR in AGN with UFOs and to explore potential connections between the BLR and a disk wind. This is the first result from a new RM campaign of Mrk 79, which was undertaken with the Lijiang 2.4 m telescope (LJT+YFOSC). SFS was adopted to remove the host-galaxy component from the spectrum and improve the measurement quality of the light curves. Reverberation analysis of several broad emission lines ($\mathrm{H}\beta \lambda 4861$, $\mathrm{H}\gamma \lambda 4340$, $\mathrm{He}\ II \lambda 4686$, and $\mathrm{He}\ I \lambda 5876$) were carried out. Based on the present campaign, we obtained the following results.

1. Mrk 79 appears to come out the faint state; the average flux of the AGN at 5100 Å is approximately a magnitude fainter than the previous record holder. We found that the variability amplitudes of the broad emission lines meet the $F_{\text{var,He II}} < F_{\text{var,He I}} < F_{\text{var,He II}}$ relation.

2. The high-ionization line of He II $\lambda 4686$ has a marginal blueshift with a velocity of $\sim 450$ km s$^{-1}$, which indicates an outflow of high-ionization gas.

3. We successfully measured the time delays of the broad $\mathrm{H}\beta \lambda 4861$, $\mathrm{H}\gamma \lambda 4340$, $\mathrm{He}\ II \lambda 4686$, and $\mathrm{He}\ I \lambda 5876$ emission lines with respect to the continuum variation. The optimum lags of $\mathrm{H}\gamma \lambda 4340$, $\mathrm{H}\beta \lambda 4861$, and $\mathrm{He}\ I \lambda 5876$ lines marginally show an ionization stratification of the BLR. The lag of the He II $\lambda 4686$ line approximates zero, which is consistent with previous results.

4. We simultaneously obtained the velocity-resolved lag profiles of the broad $\mathrm{H}\gamma \lambda 4340$, $\mathrm{H}\beta \lambda 4861$, and $\mathrm{He}\ I \lambda 5876$ emission lines for the first time, which show almost the same kinematic signatures. Specifically, the high-velocity gas in the wings exhibits a shorter lag than the low-velocity gas. However, the lag in the red wing is slightly larger than the lag in the blue wing, and the largest lag occurs in the red side. These complicated signatures could suggest that the BLR of Keplerian motion in Mrk 79 probably exists as an outflow gas motion during the monitoring period.

5. Based on the velocity width and time delay of the broad $\mathrm{H}\beta \lambda 4861$ line, we measured a BH mass of $M = 5.13^{+1.35}_{-1.53} \times 10^7 M_{\odot}$ for Mrk 79. This value is consistent with the estimate from the $M - c_d\beta$ relation. Using this BH mass and an optical luminosity at 5100 Å $L_{5100} = (1.45 \pm 0.14) \times 10^{43}$ erg s$^{-1}$, we estimated accretion rates of $\dot{M} = (0.05 \pm 0.02) L_{\text{Edd}} c^{-2}$. Mrk 79 is a sub-Eddington accreting AGN.
6. We found that the current \( R_{\text{BLR}} - L_{5100} \) relation of Mrk 79 reverberation deviates from both the canonical \( R_{\text{BLR}} - L_{5100} \) (slope = 0.53) and NGC 5548’s \( R_{\text{BLR}} - L_{5100} \) (slope = 0.86) relationships. More and dense RM campaigns are necessary to construct a robust \( R_{\text{BLR}} - L_{5100} \) relationship for Mrk 79.

As discussed in Section 4, although we do not know whether blueshifted UV absorbers/emitters exist in Mrk 79 in absence of a UV spectrum, many findings including UFOs, warm absorbers, and the BLR kinematics of the high- and low-ionization gas, indicate that the BLR of Mrk 79 probably originates from a disk wind launched from the accretion disk. Nevertheless, simultaneous observations of multiband spectra are necessary to confirm this speculation.

We are grateful to the referee for useful suggestions that improved the manuscript. We acknowledge the support of the staff of the Lijiang 2.4 m telescope. Funding for the telescope has been provided by CAS and the People’s Government of Yunnan Province. This research is supported in part by the National Key Program for Science and Technology Research and Development of China (grants 2016YFA0400701 and 2016YFA0400702). L.C.H. acknowledges financial support from the National Natural Science Foundation of China (NSFC; 11721303). K.X.L. acknowledges financial support from the NSF (11703077) and from the Light of West China Program provided by CAS (No. Y7XB016001). M.K. was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. 2017R1C1B2002879). W.H.B. acknowledges financial support from the NSFC (11973029).

Appendix A
Insight into the Spectroscopy and Calibration

To qualitatively study the apparent variation in the flux of the host galaxy and the [O III] \( \lambda 5007 \) emission mentioned in Sections 3.1 and 3.4, we have insight into the details of spectroscopy and flux calibration in this appendix. Mrk 79 consists of the AGN (including the BLR), the host galaxy, and the [O III] emission region (i.e., NLR: the narrow-line region), which is observed along with the comparison star simultaneously. At first, we simply considered the size of different components. The AGN including the BLR along with the comparison star are point sources; the intrinsic size of a point source approximates \( 0'' \) in remote distance. For the NLR and the host galaxy, we note that Peterson et al. (1995) have produced models of the surface-brightness distribution of the NLR and host-galaxy distribution from ground-based images in NGC 4151 and NGC 5548, and found that (1) the NLR of NGC 5548 is point-like source; (2) the NLR of NGC 4151 is a slightly extended source. Based on the growth curve for the [O III] \( \lambda 5007 \) flux distribution constructed by Peterson et al. (1995), we estimated the radius (defined by 80% of the integrated [O III] \( \lambda 5007 \) flux) of the [O III] emission region in NGC 4151 (\( \sim 1''5 \)); and (3) the host galaxy is a very extended source; this is consistent with the results of HST image decomposition for the local AGNs (see Bentz et al. 2009a; Kim et al. 2017). In Mrk 79, based on an HST image of the [O III] emission, Schmitt et al. (2003a) measured the effective radius (defined by 50% of the integrated [O III] \( \lambda 5007 \) flux), the extent of the photometric semimajor and semiminor axes of the [O III] emission (see Table 3 of Schmitt et al. 2003a). The semimajor axis, which is roughly perpendicular to our long slit (see Figure 8 of Schmitt et al. 2003a; the position angle of our long slit is \( -99^\circ \)), has a size of \( 2''1 \), comparable to the width of slit. This valuable measurement shows that the NLR of Mrk 79 along with parts of other AGNs is a slightly extended source. For AGNs with a slightly extended NLR and observed with a broad spectrograph slit of 5''0 (adopted by many previous RM campaigns, see Table 12 of Bentz et al. 2013), the standard spectral calibration method using the [O III] \( \lambda 5007 \) as a calibrator provides precise internal flux calibration of spectra (see Peterson et al. 1995; Fausnaugh 2017), because the broad spectrograph slit integrally observed the [O III] \( \lambda 5007 \) emission of AGNs. This is not the case for a small spectrograph slit (\( 2''5 \)); the seeing-induced aperture effects will cause apparent variations in the flux of an extended source. We give a quantitative analysis about this point next, in fact, which is similar to Peterson et al.’s (1995) analysis of aperture effects on the accuracy of ground-based spectrophotometry.

Figure 10 is a spectroscopic schematic diagram for showing the flux variation of different components in the slit. We use red and blue Gaussian profiles to present the surface-brightness distribution of these components broadened by different seeing (in practice, the slightly or very extended source has a flatter surface-brightness distribution than a Gaussian profile; see Peterson et al. 1995). For each component, the area surrounded by red and blue Gaussians within the small slit present the fractions of light loss caused by varying seeing. Figure 10 shows that the fractions of light loss due to varying observing conditions (e.g., seeing) are dependent on the size of the object (i.e., the width of the surface-brightness distribution), seeing, and the width of slit (also see Peterson et al. 1995). If we use \( \psi_{\text{star}}, \psi_{\text{AGN}}, \psi_{[\text{O III}]}, \) and \( \psi_{\text{gal}} \) to represent the percentage of flux remaining in the aperture for different components, the observed flux can be described by

\[
F_{\text{obs}}^{\text{star}} = \psi_{\text{star}} \times F_{\text{abs}}^{\text{star}} \tag{7}
\]

for the comparison star,

\[
F_{\text{obs}}^{\text{AGN}} = \psi_{\text{AGN}} \times F_{\text{abs}}^{\text{AGN}} \tag{8}
\]

for the AGN,

\[
F_{\text{obs}}^{[\text{O III}]} = \psi_{[\text{O III}]} \times F_{\text{abs}}^{[\text{O III}]} \tag{9}
\]

for [O III] \( \lambda 5007 \) (from the extended NLR), and

\[
F_{\text{obs}}^{\text{gal}} = \psi_{\text{gal}} \times F_{\text{abs}}^{\text{gal}} \tag{10}
\]

for the host galaxy, where \( F_{\text{abs}} \) are the absolute fluxes of these components.

The observed flux \( F_{\text{obs}} \) is corrected by multiplying by the flux-calibration factor; the factor is obtained by comparing the absolute flux to the observed flux of the comparison star (Maoz et al. 1990; Kaspi et al. 2000; Du et al. 2014), that is the calibrated flux

\[
F_{\text{cal}} = F_{\text{obs}} \times \frac{F_{\text{abs}}^{\text{star}}}{F_{\text{obs}}^{\text{star}}} = \frac{1}{\psi_{\text{star}}} \times F_{\text{obs}}. \tag{11}
\]
Therefore, we deduced the calibrated flux of the AGN

\[
F_{\text{cal}}^{\text{AGN}} = \frac{\psi_{\text{AGN}}}{\psi_{\text{star}}} \times F_{\text{obs}}^{\text{AGN}}
\]

\[= \frac{\psi_{\text{AGN}}}{\psi_{\text{star}}} \times F_{\text{abs}}^{\text{AGN}} = f_{\text{cal}}^{\text{AGN}} \times F_{\text{abs}}^{\text{AGN}}, \tag{12}
\]

the extended NLR

\[
F_{\text{cal}}^{[\text{O}\,\text{III}]} = \frac{\psi_{[\text{O}\,\text{III}]}_{\text{star}}}{\psi_{[\text{O}\,\text{III}]}_{\text{star}}} \times F_{\text{abs}}^{[\text{O}\,\text{III}]} = f_{\text{cal}}^{[\text{O}\,\text{III}]} \times F_{\text{abs}}^{[\text{O}\,\text{III}}], \tag{13}
\]

and the host galaxy

\[
F_{\text{cal}}^{\text{gal}} = \frac{\psi_{\text{gal}}}{\psi_{\text{star}}} \times F_{\text{obs}}^{\text{gal}}
\]

\[= \frac{\psi_{\text{gal}}}{\psi_{\text{star}}} \times F_{\text{abs}}^{\text{gal}} = f_{\text{cal}}^{\text{gal}} \times F_{\text{abs}}^{\text{gal}}, \tag{14}
\]

In each, \(f_{\text{cal}}\) is the flux-calibration factor of the different components.

Figure 10 also shows that for two point sources (the comparison star and AGN) kept in a line parallel to the slit, the fractions of light loss due to varying seeing are identical. However, for extended components (the [O\text{ III}] emission region and the host galaxy) in the same slit, the fractions of light loss due to varying seeing are less than for a point source (a similar analysis of aperture effects is addressed in Section 2.1 of Peterson et al. 1995). In this case, for Mrk 79, the radii of different components including the AGN, the NLR, and the host galaxy, meet the \(R_{\text{AGN}}(\sim0\arcsec) < R_{\text{NLR}}(\sim2\arcsec) < R_{\text{gal}}(\sim5\arcsec)\) relation. When seeing increases, the percentages of flux remaining in the aperture meet the \(\psi_{\text{AGN}} = \psi_{\text{NLR}} < \psi_{\text{gal}}\) relation. The result is that the flux-calibration factors meet the \(1 = f_{\text{cal}}^{\text{AGN}} < f_{\text{cal}}^{[\text{O}\,\text{III}]} < f_{\text{cal}}^{\text{gal}}\) relation. That is, the most extended component has the largest flux calibration factor. Consequently, (1) the flux-calibration factor of an extended component should correlate with seeing, that is the calibrated fluxes including \(F_{\text{cal}}^{[\text{O}\,\text{III}]}\) and \(F_{\text{cal}}^{\text{gal}}\) (Equation (13) and (14)) should correlate with seeing because the absolute flux (including \(F_{\text{cal}}^{[\text{O}\,\text{III}]}\) and \(F_{\text{cal}}^{\text{gal}}\)) is constant; and (2) the host-galaxy fluxes \(F_{\text{cal}}^{\text{gal}}\) should be more scattered than \([\text{O}\,\text{III}]\)'s fluxes \(F_{\text{cal}}^{[\text{O}\,\text{III}]}\), since \(f_{\text{cal}}^{\text{gal}}\) is larger than \(f_{\text{cal}}^{[\text{O}\,\text{III}]}\) with varying seeing.

In order to test the above results from the perspective of observations, we measured the width (FWHM\text{star}) of star’s flux distribution from the short exposure image, which was observed before and near the spectroscopy. Panel (c) shows the variation of FWHM\text{star}.
variation of FWHM\textsubscript{star}. Actually, these results are consistent
with the above analysis, and show that the [O\textsc{iii}] emission region in Mrk 79 is a slightly extended source. Therefore, for a narrow slit, the varying observing conditions will give rise to the apparent variation in flux of the extended components, so that the [O\textsc{iii}] emission remains in the rms spectrum and its fluxes have a scatter of 5%.

Figure 12. Relation between the fluxes of extended components ($F_{\text{O III}}$ and $F_{\text{gal}}$) and FWHM\textsubscript{star} variation. Spearman’s rank-order correlation coefficient ($\rho$) and the $p$-value ($p$) are noted in the panels.

Appendix B
Velocity-resolved RM

In Section 3.8, we presented the procedure of velocity-resolved RM. In this appendix, we provide the velocity-dependent light curves and cross-correlation analysis including H\textsc{$\beta$} $\lambda$4861, H\textsc{\textgamma} $\lambda$4340, He \textsc{ii} $\lambda$4686, and He \textsc{i} $\lambda$5876 (see Figures 13–16).
Figure 13. Velocity-resolved reverberation mapping for Hβ. The left panels (a)–(j) show the light curves of AGN continuum at 5100 Å and the broad Hβ emission line of each velocity bin, respectively. We note the variability amplitude of the light curves in panels (b)–(j). The right panels (aa)–(ja) correspond to the ACF of continuum at 5100 Å and the CCF between the light curve of each velocity bin (b)–(j) and the continuum variation (a), respectively. We note the maximum correlation coefficients ($r_{\text{max}}$) in panels (b)–(j). Monte Carlo simulations of the centroid (blue) are overplotted in panels (ba)–(ja). Bin number (Bin 1–9) is a one-to-one correspondence with Figure 7.
Figure 14. Same as Figure 13, but for the broad Hγ emission line.
Figure 15. Same as Figure 13, but for the broad He II emission line.
Figure 16. Same as Figure 13, but for the broad He I emission line.
