Reverberation Mapping of Changing-look Active Galactic Nucleus NGC 3516

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Received 2020 August 14; revised 2020 December 29; accepted 2020 December 31; published 2021 March 2

Abstract

The changes of broad emission lines should be a crucial issue in understanding the physical properties of changing-look active galactic nuclei (CL-AGNs). Here we present the results of an intensive and homogeneous 6 month long reverberation mapping (RM) monitoring campaign during a low-activity state of the CL-AGN Seyfert galaxy NGC 3516. Photometric and spectroscopic monitoring was carried out during 2018–2019 with the Lijiang 2.4 m telescope. The sampling is 2 days in most nights, and the average sampling is ~3 days. The rest-frame time lags of Hα and Hβ are $\tau_{H\alpha} = 7.56^{+4.24}_{-2.10}$ and $\tau_{H\beta} = 7.50^{+2.05}_{-0.77}$ days, respectively. From an rms Hβ line dispersion of $\sigma_{line} = 1713.3 \pm 46.7$ km s$^{-1}$ and a virial factor of $f_v = 5.5$, the central black hole mass of NGC 3516 is estimated to be $M_{BH} = 2.4^{+0.7}_{-0.3} \times 10^7 M_\odot$, which is in agreement with previous estimates. The velocity-resolved delays show that the time lags increase toward negative velocity for both Hα and Hβ. The velocity-resolved RM of Hα is done for the first time. These RM results are consistent with other observations before the spectral-type change, indicating a basically constant broad-line region structure during the CL process. The CL model of changes of accretion rate seems to be favored by long-term Hβ variability and RM observations of NGC 3516.

Unified Astronomy Thesaurus concepts: Active galaxies (17); Photometry (1234); Reverberation mapping (2019); Seyfert galaxies (1447); Spectroscopy (1558); Supermassive black holes (1663)

Supporting material: machine-readable table

1. Introduction

Seyfert galaxies, a subset of active galactic nuclei (AGNs), were first reported by Seyfert (1943). Depending on the relative widths of Balmer and forbidden lines, Khachikan & Weedman (1974) separated the Seyfert galaxies into two subclasses, type 1 and type 2. The Balmer lines in type 1 are broader than the forbidden lines, while all the lines in type 2 have comparable widths. Additionally, some sources with strong narrow lines and weak broad lines are classified as types 1.8 and 1.9 (Osterbrock 1981). In the framework of the unification scheme (Antonucci 1993), the various types of AGNs are caused by different torus orientations with respect to the line of sight (LOS). The observational evidence of this concept is some spectropolarimetric observations detected the hidden broad emission lines (BELs) in some type 2 AGNs (e.g., Antonucci & Miller 1985; Miller & Goodrich 1990; Tran et al. 1992). However, the deeper spectropolarimetry found numerous type 2 AGNs without broad components and the absence of spectropolarimetric BELs challenged our understanding of the exact physical processes (e.g., Tran 2003; Wu et al. 2011). A handful of AGNs, so-called changing-look AGNs (CL-AGNs), may shed light on some intrinsic properties. The term “changing-look” originated from X-ray observations in which sources changed from Compton-thin to Compton-thick on timescales of years, or vice versa (e.g., Matt et al. 2003; LaMassa et al. 2015, 2017). The optical spectroscopic observations indicate that these objects are usually accompanied by a significant change in spectral type, i.e., the BELs disappear or reappear, and a number of subsequent CL-AGNs are identified by optical spectrum (e.g., Storchi-Bergmann et al. 1993; Aretxaga et al. 1999; Eracleous & Halpern 2001; Denney et al. 2014; Kim et al. 2018; Wang et al. 2018; Shapovalova et al. 2019).

The mechanisms of CL-AGNs are still debated. Early explanations mainly focus on the change in obscuration (Bianchi et al. 2005), while some recent studies favor the change of accretion rate (Stern et al. 2018; Sniegowska et al. 2020). Photoionization research shows that the CL behavior in CL quasars can be fully explained by the photoionization responses of the BELs to the extreme variability of the ionizing continuum (Guo et al. 2020). Besides, several objects can be interpreted as tidal disruption events (Merloni et al. 2015; Ricci et al. 2020). All of the models can generate significant variance in the observed intensity of continuum and emission lines. These models might be restricted by statistical studies after extending the sample of CL-AGNs. Several groups have been devoted to searching for new CL-AGNs, and tens of candidates have been discovered based on large optical and X-ray surveys, such as the Sloan Digital Sky Survey (e.g., LaMassa et al. 2015; MacLeod et al. 2016; Runbaugh et al. 2018; Hon et al. 2020), intermediate Palomar Transient Factory (Gezari et al. 2017), Pan-STARRS1 (MacLeod et al. 2019), Catalina Real-time Transient Survey (Yang et al. 2018), and XMM-Newton...
slew survey (Zetzl et al. 2018; Kollatschny et al. 2020). In the future, the Large Synoptic Survey Telescope will regularly monitor millions of AGNs, and the number of CL-AGNs will further increase. The evolution of the AGN type can be well studied if we obtain continuous multiwavelength data of the complete changing process, and the development of time-domain surveys makes it possible to achieve this. The brightening of NGC 2617 (Shappee et al. 2014) and IES 1927+654 (Trakhtenbrot et al. 2019) triggered the alert of the All-Sky Automated Survey for Supernovae,7 and follow-up observations confirmed these two CL-AGNs. However, so far, there are only small available data sets for most detected CL-AGNs, especially around the critical regime of transition between types 1 and 2. Moreover, previous studies rarely gave the change of geometry and kinematics in broad-line regions (BLRs).

To date, the GRAVITY interferometer can directly resolve the spatial profile of a BLR, but only 3C 273 has been observed (Sturm et al. 2018). Another powerful technique to investigate the size, geometry, and kinematics of a BLR is reverberation mapping (RM; e.g., Blandford & McKee 1982; Peterson 1993). The technique is based on a widely accepted assumption that BELs are generated through photoionization driven by the central continuum radiation. Thus, a delayed correlation and a time lag of \( \tau \) (in the rest frame) will be expected between the light curves (LCs) of AGN continua and BELs. The time lag is caused by the light travel time, and the size of the BLR is \( R_{\text{BLR}} = c\tau \), where \( c \) is the light speed. Based on the assumption of virialized motion of gas clouds in the BLR, the virial mass of the central black hole is expressed as

\[
M_{\text{BH}} = \frac{c \tau v^2}{G},
\]

where \( G \) is the gravitational constant, \( v \) is the BEL velocity width, and \( f \) is the virial factor depending on the geometry and kinematics of the BLR (Peterson 1993). Here \( f \) can be determined with the \( M_\bullet - \sigma_\star \) relation for the low-z inactive galaxies, quiescent galaxies, and/or reverberation-mapped AGNs, where \( \sigma_\star \) is the stellar velocity dispersion of the galaxy bulge (e.g., Tremaine et al. 2002; Onken et al. 2004; Woo et al. 2013, 2015; Piotrovich et al. 2015). Recently, Liu et al. (2017) proposed a new method to measure \( f \) using the gravitationally redshifted BELs. Several known CL-AGNs have been studied with RM, including Mrk 590 (Peterson et al. 1998), NGC 3516 (Denney et al. 2010), NGC 2617 (Fausnaugh et al. 2017), and NGC 4151 (De Rosa et al. 2018). Okniansky et al. (2019) confirmed NGC 1566 to be a CL Seyfert galaxy. Since the BELs are weak during type 2, all of the previous RM campaigns were only carried out in the type 1 state. Therefore, the difference of the BLR before and after the change in type is still unclear.

One of the first reported Seyfert galaxies characterized by complex emission lines is NGC 3516 (\( z = 0.00884 \)). The Balmer lines show a clear double-peak component, which is usually regarded as the contribution of the outer parts of an accretion disk (e.g., Popović et al. 2002; Storchi-Bergmann et al. 2017), but the detailed structure of the emitting region is still under debate. In the first 5 months of 1990, Wanders et al. (1993) carried out spectroscopic monitoring of the object with 21 spectra and gave a time lag of \( \tau_{H\beta} = 7_{-3}^{+3} \) days. A high-cadence RM campaign in 2007 gave \( \tau_{H\beta} = 7.43_{-0.99}^{+1.02} \) days (Denney et al. 2010). During the first half of 2012, De Rosa et al. (2018) obtained a time lag of \( \tau_{H\beta} = 8.11_{-0.58}^{+0.75} \) days, which is well consistent with the previous results. Unlike other AGNs, e.g., NGC 5548 with a variable BLR size (e.g., Peterson et al. 2002; Lu et al. 2016; Kovačević et al. 2018), the H\( \beta \) time lag of NGC 3516 is basically constant over 20 yr. The long-term monitoring campaign confirmed that the object is a CL-AGN after 2014 (Shapovalova et al. 2019). The BELs nearly disappeared, and the continuum declined by more than a factor of 2. The X-ray observations of Suzaku also detected a faint phase in the period of 2013–2014 (Noda et al. 2016). Interestingly, Ilić et al. (2020) reported a new optical flare and several coronal lines at the end of 2019, indicating that the object may switch on again. The repeat spectral transition in such short timescales hints that its CL phenomenon is probably driven by changes in accretion rate. Kraemer et al. (2002) found eight absorption troughs in the UV band, and this supports the outflows in NGC 3516. Dunn et al. (2018) found a clear change in one of the absorption troughs using the Hubble Space Telescope (HST) Cosmic Origins Spectrograph spectrum in 2011, and it was interpreted as bulk motion.

The data used in this paper are from a new RM campaign that aims to investigate the disklike BLRs. We present the general results of RM and discuss the origin of CL. The structure of the BLR will be studied in the next paper. The information on observations and data reduction is described in Section 2; the LCs, time-series analyses, black hole masses, and velocity-resolved delays are presented in Section 3; a discussion is in Section 4; and a summary is in Section 5.

2. Observations and Data Reduction

From 2018 November to 2019 May, the observations of NGC 3516 were carried out with the Yunnan Faint Object Spectrograph and Camera mounted at the 2.4 m optical telescope. The telescope is located at Lijiang Observatory, Yunnan Observatories, Chinese Academy of Science. The detailed information on the telescope, instruments, and observatory was described in Wang et al. (2019) and Xin et al. (2020). The observing procedure is similar to that in Feng et al. (2020). Here we briefly describe the main points. The cadence is 2 days in most nights, and two small gaps in the beginning of the observations are caused by bad weather. In each photometric night, we would take a broadband Johnson \( B \) image before or after the spectroscopic exposure, and 59 data points were successfully observed during our monitoring campaign. Four nearby comparison stars are always in the field of view that can provide accurate calibration of the target (\(<1\%\)). The 69 spectra were obtained by Grism 14, which provides a dispersion of 1.76 Å pixel\(^{-1}\) and a wavelength coverage of 3600–7460 Å. Considering the seeing condition (~1\(\prime\)5) of the telescope, we adopted a long slit with a projected width of 2\(\prime\)5, which can minimize the effects of atmospheric differential refraction and provide a relatively high spectral resolution. For each spectroscopic observation, we simultaneously put the target and a comparison star in the slit to improve the flux calibration. We also take a spectrophotometric standard star in the night to calibrate the absolute flux of the comparison star. Besides, we employed a UV-blocking filter to eliminate the secondary spectrum. Therefore, the data around

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7 http://www.astronomy.ohio-state.edu/asassn
Hα can be used in our analysis. To evaluate the effects of the seeing and grism, we also took two additional spectra using a wide slit width (5.05″) and the low-resolution Grism 3 (0.93 Å pixel⁻¹) in different nights. We found that the two spectra of the comparison star are consistent with each other, and they are also consistent with the spectra obtained by Grism 14 in good weather conditions. Therefore, we averaged the two spectra as a fiducial spectrum that can be used to calibrate the flux of the target.

All of the raw photometric and spectroscopic data were reduced with the standard IRAF software. The aperture radius of photometry was 6″, and the differential magnitudes were obtained using the photometric comparison stars. The one-dimensional spectra of the target and comparison star were extracted from a uniform aperture radius of 5.43. Van Groningen & Wanders (1992) calibrated the spectral flux using the [O III] emission line, and this choice is widely adopted in many RM campaigns (e.g., Bentz et al. 2009b; Hu et al. 2016; Fausnaugh et al. 2017; Du et al. 2018). Generally, this method needs wide slit widths for extended sources. The [O III] emitting region of NGC 3516 is larger than 10″ (see also Figure 2 in Shapovalova et al. 2019). Thus, the [O III]-based calibration approach is not suitable for our observations. All of the spectra were calibrated by the spectrum of the comparison star. We corrected the Galactic extinction of the spectra using the dust map of Schlegel et al. (1998) and the extinction curve of Fitzpatrick (1999). Finally, the mean spectrum is shown in the top panel of Figure 1. We also measured the rms spectrum (see the bottom panel of Figure 1) using the same method as in Peterson et al. (2004). Note that the variance of the seeing and calibration accuracy of the wavelength will affect the shapes of the narrow lines (see also Peterson et al. 2004); we therefore subtracted the fitted narrow lines and host components before our calculation of the rms spectrum (see details in Section 3.3).

3. Results and Analysis

3.1. Light Curves

The B-band photometric LC is shown in the top panel of Figure 2, and the error bars are calculated as in Liu et al. (2019), i.e., the combination of Poisson errors (from the target and comparison stars) and systematic errors (from the variation of comparison stars). The photometric data are listed in Table 1. The continuum (rest-frame 5100 Å) LC is measured from the median value between 5090 and 5110 Å. We found that the standard deviations (σs) in the continuum window are consistent with the corresponding Poisson errors. Thus, we adopted σs as the errors of continuum. For the emission-line fluxes, we first inspected the mean and rms spectra to confirm the continuum windows around each line (6400–6415 and 6760–6780 Å for Hα, 4780–4800 and 5090–5110 Å for Hβ). We then subtracted the continuum through a linear fit. The fluxes of Hα and Hβ (both broad and narrow components) were obtained by integrating 6460–6650 and 4810–4910 Å, respectively. The Poisson errors of each line can be directly measured by the IRAF. However, both continuum and emission lines should be affected by the systematic error, which might be related to weather conditions and instrument state. Following the method in Du et al. (2014), we smoothed the LCs with a median filter of five data points and then subtracted the original LCs. The systematic errors are estimated.
through the standard deviation of the residuals. The systematic errors are usually much larger than the Poisson errors due to the variation of host galaxy flux in the slit. The LCs of Hα, Hβ, and the continuum are shown in Figure 2, and the corresponding data are listed in Table 1.

3.2. Time-series Analysis

As shown in Figure 1, the starlight of the host galaxy heavily contaminates the brightness of 5100 Å, and the narrow slit width will introduce some unexpected uncertainties because of the variance of the seeing conditions. Hence, we use the photometric (B-band) data as the continuum. To estimate the light travel time lag between the continuum and lines, we employed the interpolated cross-correlation function (ICCF; White & Peterson 1994), one widely accepted method. We found that the location of the ICCF peak (τmax) is consistent with the location of the ICCF centroid above 0.8rmax, and only the centroid value was adopted in our time lag analysis. Another standard method, the Z-transformed discrete correlation function (ZDCF; Alexander 1997), was also used to measure the time lags of Hα and Hβ. The ZDCF gives results similar to those derived from the ICCF. The results of the ICCF in our analysis are used to estimate M_BH. The time dilation is corrected via τrest = τobs/(1 + z), where z = 0.00884 (Keel 1996).

In order to estimate the uncertainties of the time lag, we employed the flux randomization/random subset selection method (Peterson et al. 2004) to build up the cross-correlation centroid distribution (CCCD). Each CCCD is generated by 10,000 Monte Carlo realizations. The lower and upper errors of the lag were determined by the 15.87% and 84.13% quantiles of the CCCD, respectively. The ICCFs and CCCDs are shown in the right panels of Figure 2. The time lags of Hα and Hβ are measured using their integrated LCs, and τrest ≈ 7.5 days (see Table 2). Our results are consistent with the previous RM results of Hβ (Wanders et al. 1993; Denney et al. 2010; De Rosa et al. 2018). For Hα and Hβ, Shapovalova et al. (2019) got time lags of ∼15–17 days, which are larger than our RM results. Also, the Hα time lag of 14 ± 2 days obtained in Wanders et al. (1993) is larger than our result of 7.5 days. However, the average sampling of the RM observations in Wanders et al. (1993) is ∼7 days, and the average sampling in Shapovalova et al. (2019) is ∼3 months for Hα and ∼2 months for Hβ. Our average sampling is ∼3 days, and then our measured time lags of 7.5 days seem more reliable.

3.3. Contamination of Host Galaxy

The contribution of the host galaxy might affect the RM results due to the extremely faint phase of NGC 3516 during our observations (Shapovalova et al. 2019). Therefore, it is important to evaluate the influence of the host galaxy on LCs. Feng et al. (2017) found that the variance of seeing will change the brightness in the aperture for the extended source. We examined the correlation between the brightness and seeing of the photometry and did not find any significant correlation. Thus, the host galaxy should marginally affect our B-band photometric LC because of the large aperture radius (6″). In terms of the spectroscopy, we fitted each spectrum using the Levenberg–Marquardt least-squares minimization technique, which is widely used to decompose the starlight (Barth et al. 2004). The LCs of photometry, Hα, Hβ, and 5100 Å (left panels). The LCs of Hα, Hβ, and 5100 Å are the integrated LCs. The right panels show ACF, ICCF (black), and CCCD (green). Fluxes of Hα and Hβ are obtained by integrating the continuum-subtracted spectra containing the narrow lines. The continuum flux density is obtained by integrating the spectra.

Figure 2. The LCs of photometry, Hα, Hβ, and 5100 Å (left panels). The LCs of Hα, Hβ, and 5100 Å are the integrated LCs. The right panels show ACF, ICCF (black), and CCCD (green). Fluxes of Hα and Hβ are obtained by integrating the continuum-subtracted spectra containing the narrow lines. The continuum flux density is obtained by integrating the spectra.
Table 1
LCs of Photometry and Lines

| JD−2,458,000 | Mag          | JD−2,458,000 | Hα    | Hβ   |
|------------|--------------|--------------|-------|------|
| 431.423843 | 2.226 ± 0.004 | 447.351852   | 106.09 ± 6.16 | 9.95 ± 0.85 |
| 433.405000 | 2.235 ± 0.004 | 448.4002     | 105.74 ± 6.16 | 11.40 ± 0.84 |
| 451.415313 | 2.238 ± 0.005 | 451.419306   | 110.15 ± 6.16 | 10.35 ± 0.83 |
| 452.427616 | 2.235 ± 0.005 | 466.464250   | 112.74 ± 6.16 | 10.90 ± 0.84 |
| 466.441007 | 2.282 ± 0.006 | 474.455787   | 94.85 ± 6.16  | 9.27 ± 0.84  |

Note. The fluxes of Hα and Hβ are in units of 10^{-14} erg s^{-1} cm^{-2}.
(This table is available in its entirety in machine-readable form.)

Table 2
Rest-frame Lags, Line Widths, and Black Hole Masses

| Line | Lag (days) | σ_line (km s^{-1}) | M_{BH} (×10^7 M_☉) |
|------|-----------|-------------------|-------------------|
| Hα   | 7.56±2.20 | 2256.8 ± 16.8     | 1823.8 ± 41.3     | 4.1±1.1        | 2.7±1.4        |
| Hβ   | 7.05±2.00 | 1881.5 ± 13.8     | 1713.3 ± 46.7     | 2.8±0.3        | 2.4±0.3        |

As an example, the fitted mean spectrum is depicted in Figure 3. Figure 4 shows the LCs of continuum and emission lines measured from the best-fitting model. The AGN continuum is measured from the fitted power law around 5100 Å, and the fluxes of Hα and Hβ are obtained by the broad components. Both the AGN and comparison star are point sources, while the host galaxy is an extended source. Thus, the effects of the seeing conditions are different for the AGN and host galaxy. The flux of the AGN can be well calibrated by the comparison star, and the host galaxy will contribute some fake variability in the continuum and narrow lines. Comparing Figures 2 and 4, the fitted results of Hα and Hβ are almost identical to the integrated results, but there is a smaller data-point scatter in the fitted continuum LC. The continuum is directly contaminated by the strong host galaxy, and this means that even small fluctuations in the host galaxy will generate large scatter in its LC. The fluxes of integrated Hα and Hβ are mainly affected by the narrow emission lines. However, the proportion of narrow lines to broad lines is much smaller than the ratio of host galaxy to AGN continuum, resulting in a small scatter in the BEL LC. Although the spectral fitting can basically remove the contribution of the host galaxy, it can also introduce extra errors. This might generate a worse LC in the case where there is a weak effect of the host galaxy (e.g., Hu et al. 2020). Indeed, the LC of the fitted Hβ (only contaminated by narrow Hβ) shows slightly larger scatter, but the LCs of the fitted Hα and continuum show smaller scatter. We found that the lags calculated from the fitted LCs are the same as the integrated results. This indicates that the contribution of the host galaxy might marginally influence our RM analysis.

3.4. Black Hole Mass

The M_{BH} can be estimated via Equation (1). Two widely used methods are employed to measure the velocity width of the BELs, including the FWHM and the line dispersion (σ_line) of the BELs. Here only σ_line is adopted to measure M_{BH} due to the irregular BELs. The finite resolution of the instrument is corrected using the FWHM of [O III]. Comparing the [O III] FWHM (∼747 km s^{-1}) in our mean spectrum and the intrinsic width of 250 km s^{-1} (Whittle 1992), we can obtain a spectral resolution of 704 km s^{-1}. Following Peterson et al. (2004), we calculated the width σ_line of each broad line from both the rms and mean spectra. The results of σ_line are given in Table 2. Onken et al. (2004) gave f_α = 5.5, which is in agreement with the value of Woo et al. (2010). Thus, we derived four values of M_{BH} for NGC 3615 (see Table 2). Our measured black hole masses are consistent with the previous RM measurements (Peterson et al. 2004; Denney et al. 2010; De Rosa et al. 2018; Shapovalova et al. 2019).

2015; Hu et al. 2016). The detailed fitting procedure is described below.

1. The fitting model consists of a single power-law continuum (f_β = C λ^α), a broad optical Fe II template from Dong et al. (2008), the host galaxy template of Bruzual & Charlot (2003), one Gaussian for broad He I λ5876 emission, two double Gaussians for broad Hα and Hβ, and tens of single Gaussians for narrow permitted lines and forbidden lines (including several coronal lines). The permitted narrow lines include Hβ, Hβ, He II λ4686, and He I λ5876, while the forbidden lines are the [O III] λλ4959, 5007 doublet, [N I] λλ5199, [Fe VII] λ721, [Fe VIII] λ6086, the [O I] λλ6300, 6363 doublet, [N II] λλ6548, 6583, and [S II] λλ6718, 6732. Throughout our fitting process, all of the narrow components are assumed to have the same profile, and the fitting range covers 4400−6800 Å in the rest frame.

2. First, we fit the mean spectrum to obtain an optimal host template. The flux ratios of the [N II] doublet λλ6583/λ6548 and [O III] doublet λ5007/λ4959 are fixed to the theoretical values of 2.96 and 3, respectively. The template of the host galaxy is fixed (except resolution) in the following fitting of the individual spectrum, and we also fit the relative flux ratios of other narrow lines to the mean spectrum. Although Ilić et al. (2020) found the variability in the coronal lines, they should not affect our fitting results. If we fix the spectral index (i.e., α) to the best-fitting value of the mean spectrum, the scatter in the LCs can be moderately reduced. The spectra of HST indicate that different Balmer lines (Hα, Hβ, and Hγ) of NGC 3516 have nearly the same profile (Devereux 2016). In the fitting, the broad Hα and Hβ are assumed to have the same redshift and width, and this will generate a better fitting result.

3. We also fit the spectra using three to four Gaussians, and the host galaxy template is replaced with the spectrum of the host component obtained by the principal component analysis method (Ilić et al. 2020). The final results from the different ways are consistent with each other.
3.5. Velocity-resolved Lags

The lags calculated from the LCs of the total flux of the BELs only represent the mean scale of the BLR. However, the detailed geometry and kinematics of the BLR are still ambiguous. We can separately measure the lags of different velocity regions (the so-called velocity-resolved RM) to recover the information of the BLR (e.g., Horne et al. 2004). The two-dimensional velocity-delay map will be provided in our future work. Here we simply divided the line flux into 10 bins in velocity space. Each bin contains equal flux in the rms spectrum. The LCs of each bin are shown in Figure 5, and the corresponding lags are plotted in Figure 6. Both H\(_\alpha\) and H\(_\beta\) show clear shorter lags toward the red side, and this trend is consistent with that obtained by H\(_\beta\) in Denney et al. (2010). The time lag of the blue side of the double-peaked H\(_\alpha\) is larger than that of the red side by \(\Delta t_{H\alpha} \approx 20\) days (see Figure 6). For the double-peaked H\(_\beta\), \(\Delta t_{H\beta} \approx 10\) days.

4. Discussion

From the comparison of the H\(_\beta\) profile observed in 1943 by Seyfert (1943) and 1967 by Andrilat (1968), it can be clearly seen that the broad H\(_\beta\) component was present and absent in the epochs of 1943 and 1967, respectively (Shapovalova et al. 2019). From 1990 to 2007, NGC 3516 showed dramatic BELs, and three RM campaigns were carried out during this period (Wanders et al. 1993; Denney et al. 2010; Shapovalova et al. 2019). De Rosa et al. (2018) provided RM data of H\(_\beta\), obtained during 2012, for NGC 3516. Both the mean and rms spectra show a significant broad H\(_\beta\) component (see Figure 4 in De Rosa et al. 2018), which means that NGC 3516 may be a type 1 AGN in 2012. From 2014 to 2018, NGC 3516 was in states with very weak H\(_\beta\) BELs (Shapovalova et al. 2019). Reliable lags of BELs are detected by the high-quality data from our RM campaign of NGC 3516 from 2018 November to 2019 May. Thus, NGC 3516 may be the first CL-AGN that has RM data before and after changing its type. These H\(_\beta\) variability and RM results may provide some clues to the BLR and the mechanism of the changes in type.

According to LaMassa et al. (2015), the obscuration timescale can be estimated as the crossing time for an intervening dust cloud orbiting outside a BLR,

\[
t_{\text{cross}} = 0.07 \left( \frac{r_{\text{orb}}}{1\text{Lt-day}} \right)^{3/2} M_8^{-1/2} \arcsin \left( \frac{r_{\text{src}}}{r_{\text{orb}}} \right) \text{yr},
\]

where \(r_{\text{orb}}\) is the orbital radius of the foreground cloud on a circular Keplerian orbit around the central black hole, \(M_8\) is the black hole mass in units of \(10^8 M_\odot\), and \(r_{\text{src}}\) is the true size of the BLR. The foreground cloud should be placed at \(r_{\text{orb}} \geq 3r_{\text{BLR}}\), so that it can cover a substantial portion of the gas in the BLR, specifically gas at low velocities that contributes flux to the cores of the line profile (LaMassa et al. 2015). Seyfert 1 galaxy PGC 50427 has a ratio of \(r_{\text{dt}}/r_{\text{BLR}} = 2.4\) (Pozo Nuñez et al. 2015), where \(r_{\text{dt}}\) is a dust torus radius. The rest-frame 5100 Å AGN luminosities at the epochs of the H\(_\beta\) BLR and dust lag measurement are \(L(5100 \text{ Å}) \approx 10^{43} \text{ erg s}^{-1} \text{ cm}^{-2}\) for NGC 5548 with \(r_{\text{dt}}/r_{\text{BLR}} = 4.4\) (Kokubo & Minezaki 2020). Mandal et al.
(2021) found that $r_{\text{dt}}$ is about a factor of 5.3 times larger than $r_{\text{BLR}}$ for Seyfert 1 galaxy Z229-15. The dust torus innermost radii are generally larger compared to the H$\beta$ BLR radii by a factor of ~4 for dust reverberation-mapped Seyfert galaxies (Kokubo & Minezaki 2020). Object NGC 3516 has $r_{\text{dt}} = 52.5$ lt-days with $L(5100) = 10^{42.63}$ erg s$^{-1}$ cm$^{-2}$ (Kokubo & Minezaki 2020) and $r_{\text{BLR}} = 7.5$ lt-days with $L(5100) = 10^{42.75}$ erg s$^{-1}$ cm$^{-2}$ obtained in our observations. Thus, it is appropriate to use $r_{\text{dt}} = 52.5$ and $r_{\text{BLR}} = 7.5$ lt-days in Equation (2). Using $M_8 = 0.24$ for the H$\beta$ BEL, $t_{\text{cross}} = 3.9$ yr for NGC 3516, i.e., the “disappearance” timescale of the H$\beta$ BEL is about 4 yr.

The orbital period of the dust cloud $P_{\text{orb}} = 0.228M_8^{1/2}(r_{\text{dt}}/1\text{lt-day})^{3/2}$ yr = 177 yr for NGC 3516. The ratio of appearance of the H$\beta$ BEL is $(P_{\text{orb}} - t_{\text{cross}})/t_{\text{cross}} = 44$. Object NGC 3516 has the H$\beta$ BEL from 1997 to 2007 (see Figure 12 in Shapovalova et al. 2019) and during the first half of 2012 (De Rosa et al. 2018). The disappearance of the H$\beta$ BEL is from 2014 to 2018 (see Figure 12 in Shapovalova et al. 2019). Our observations of NGC 3516 from 2018 November show the H$\beta$ BEL, as well as the H$\alpha$ BEL, again. Assuming its appearance from 1997 to 2012 and its disappearance from 2013 to 2018, the ratio of appearance to disappearance of the H$\beta$ BEL is 3, which is much smaller than 44. If assuming its appearance from 1990 to 2012, the ratio is 4.4, which is also much smaller than 44. If NGC 3516 was always a Seyfert 1 galaxy after 1967 and before 2013, the upper time limit of the H$\beta$ BEL appearance is from 1968 to 2012, and then the ratio is $\lesssim 8.8$, which is smaller than 44. The above results are only true for a single cloud. If considering 10 clouds with similar orbital elements that might obscure the BLR on the same timescale, $(P_{\text{orb}} - 10t_{\text{cross}})/t_{\text{cross}} = 3.5$, which is not inconsistent with the roughly estimated ratios of 3–8.8. In addition, $t_{\text{cross}} \approx 4$ yr is roughly consistent with the H$\beta$ BEL disappearance timescale of about 5 yr. These results significantly depend on the baseline and sampling of spectroscopic observations. The available spectral data could not determine whether the obscuration model of CL-AGNs might be favored or disfavored for NGC 3516. The appearance and disappearance timescales of the H$\beta$ BEL and their ratio may be used to test the obscuration model of CL-AGNs with future spectroscopic monitoring with a sampling of several months.

Esin et al. (1997) proposed a two-zone disk model, including an advection-dominated accretion flow within a transition radius $R_t$ and an outer standard thin disk. A change of $R_t$ may generate a transition in the accretion regime. Ai et al. (2020) found a similarity in the X-ray spectral evolution between CL-AGNs and black hole X-ray binaries, which implies that the observed CL-AGN phenomena may be related to the state transition in accretion physics. The hard X-ray emission from NGC 3516 (e.g., Ilić et al. 2020) requires an additional component than a standard thin disk, such as a corona, advection-dominated accretion flow, or hot accretion flow (see review by Yuan & Narayan 2014). The X-ray observations of NGC 3516 show photon indices of $\Gamma = 1.75^{+0.08}_{-0.02}$ on 2013 May 23–24 and $\Gamma = 1.72^{+0.08}_{-0.12}$ on 2009 October 28 (Noda et al. 2016). On average, the photon flux on 2013 May 23–24 is higher by a factor of about 2 than that on 2009 October 28 (see Figure 2 in Noda et al. 2016). This flux difference and the consistent $\Gamma$ indicate that the obscuration model of CL-AGNs
might not be favored for NGC 3516. The latest research shows that the X-ray variability observed in CL-AGNs is produced by accretion disk structure and accretion rate changes (Igarashi et al. 2020). The latest photoionization calculations produce a natural sequence of successive weakening of H$\alpha$ and H$\beta$ when the ionizing continuum decreases (Guo et al. 2020). As the BELs in NGC 3516 are strong, or NGC 3516 is a Seyfert 1 galaxy, the optical spectrum shows the appearance of a strong excess of continuum shortward of 4200 Å compared to that in the disappearance of the BELs (Devereux 2016; Shapovalova et al. 2019). This strong excess is contributed by the pure AGNs with strong BELs, because the host galaxy spectrum will be very low in the same wavelength regime (see Figure 3 in Shapovalova et al. 2019). The main difference between the obscuration origin and the accretion rate origin of CL-AGNs is likely the dust torus radius changing with the AGN ultraviolet-optical luminosity. The luminosity decrease of CL-AGN Seyfert 1 galaxy Mrk 590 is interpreted as an intrinsic change in the mass accretion rate of the black hole, switching between different accretion modes, might be favored as the CL origin in NGC 3516.

The strong host galaxy might weaken the intrinsic relative variation amplitudes of the AGN continuum. When the AGN is weaker than the host galaxy, this weakening will obviously influence the CCFs between the 5100 Å and BEL LCs and then the relevant time lags of the BELs. Figure 3 shows a strong host galaxy contribution (>60%) in the continuum of NGC 3516. The relative variation amplitudes of the 5100 Å integrated LCs are smaller than those of the 5100 Å best-fit LCs (see Figures 2 and 4). The B-band photometric LCs reflect the 5100 Å variations of the pure AGN, because the seeing effect on the photometric LCs is slight due to the large photometric aperture that basically reaches the border of the host galaxy. However, the seeing effect on the spectroscopic 5100 Å LCs is serious because of the narrow slit and the brightness distribution of the host galaxy. Ultimately, the host galaxy in fluences the spectroscopic 5100 Å LCs, as the AGN is weaker than the host galaxy. The influence of the host galaxy can be weakened in the spectral decomposition best-fit LCs but cannot be completely eliminated. Thus, the B-band LCs have more clear structures than the 5100 Å integrated LCs in Figures 2 and 4, and the CCF between the B band and 5100 Å LCs in Figure 4 is better than that in Figure 2. These clear structures are important to get the reliable time lags of BELs through the CCF analysis. That is the reason why the 5100 Å continuum LCs are replaced by the B-band LCs in Figure 4.
with the photometric LCs in the RM research of weaker AGNs with the stronger host galaxy.

In our RM campaign of NGC 3516, Hβ shows a lag of τ_{Hβ} = \(7.50^{+3.35}_{-0.77}\) days, which is well consistent with the previous RM results (see also Section 1). The measured radii of the BLR in NGC 3516 are basically constant for about 30 yr. According to the photoionization model of BELs and the radius–luminosity relationship of AGNs established by the RM observations (e.g., Kaspi et al. 2000; Bentz et al. 2009a, 2013), the BLR sizes of Hα and Hβ should change with the continuum luminosity variations. Our measured values of \(r_{BLR}\) for NGC 3516 are basically consistent with those derived in Denney et al. (2010). However, the 5100 Å and Hβ fluxes in our observations are lower than those obtained in 2007 (Denney et al. 2010). It seems that \(r_{BLR}\) did not change with the luminosity variations. Our rms spectrum gives an Hβ velocity dispersion of 1713.3 ± 46.7 km s\(^{-1}\), which is consistent with the \(\sigma_{rms}(\text{H}\beta) = 1591 ± 10\) km s\(^{-1}\) obtained in Denney et al. (2010). Also, it seems that the line width \(\nu\) did not change with the luminosity variations. Moreover, our values of \(r_{BLR}\) are consistent with the results of the other two RM observations in 1990 (Wanders et al. 1993) and 2012 (De Rosa et al. 2018). Furthermore, our RM observations show \(\tau_{H\alpha}/\tau_{H\beta} = 1\) for NGC 3516. If the BLR was a narrow belt, it would be easy to understand the above results. Based on the photoionization assumption of BELs, the \(r_{BLR}\) of a narrow belt should not change as the 5100 Å continuum (as a proxy of the ionizing continuum) varies because there is not enough space to change the position of the optimal photoionization zone when the continuum intensity varies. In terms of the BLR, NGC 3516 might be very similar to NGC 1097, in which the elliptical ring is very narrow (Eracleous et al. 1995). However, no RM observation was run during the dim state from 2014 to 2018 (e.g., Shapovalova et al. 2019), and we cannot determine whether \(r_{BLR}\) is equal for the bright and dim states. Thus, the suggestion of a narrow belt of the BLR needs to be tested by the RM observations during a period of being a Seyfert 2 galaxy with the larger telescopes.

The velocity-resolved RM of Hα is done for the first time in our RM observations of NGC 3516. Our results show that the lag of Hα is the same as that of Hβ, and the velocity-resolved lags are also consistent with each other (see Figure 6), indicating the same geometry and kinematics of the BLR for Hα and Hβ. Figure 6 shows that the lags gradually increase from 3000 to 3000 km s\(^{-1}\), which is generally regarded as the signature of inflow. Also, this velocity-resolved lag trend might be generated by an elliptical disklke BLR or a circular disklke BLR plus a spiral armlike BLR. The double-peaked Hβ and Hα BELs appear in the mean (see Figure 3) and rms (see Figure 6) spectra and have \(\tau_{H\alpha}/\tau_{H\beta} = 1\). Double-peaked BELs were predicted and fitted well by the elliptical disk model (Eracleous et al. 1995). Thus, the BLR in NGC 3516 might be an elliptical disklke one. The geometry and kinematics of the BLR during our observation period might be consistent with those obtained in Denney et al. (2010) due to the similar velocity-resolved Hβ lag maps measured in our and their work. Under pure recombination, all of the broad Balmer lines are predicted to originate from the same region, but in practice, the Balmer lines of most AGNs usually show a stratified structure that may be caused by the optical depth effects within the BLR; i.e., the optical depth of Hα is largest, followed by Hβ, and so on through the Balmer series (e.g., Netzer 1975; Rees et al. 1989; Korista & Goad 2004; Bentz et al. 2010). Bentz et al. (2010) found a mean ratio of \(\tau_{H\alpha}/\tau_{H\beta} = 1.54\) for 13 nearby Seyfert 1 galaxies and \(\tau_{H\alpha} > \tau_{H\beta}\) except for Mrk 142 (see their Table 13). Also, the consistent lags of the Balmer lines were...
detected in some other AGNs, such as NGC 4051 and Mrk 374 (Fausnaugh et al. 2017) and PKS 1510–089 (Rakshit 2020). Whether the lags of the Balmer lines are consistent with each other might constrain the physical conditions within the BLRs of CL-AGNs, e.g., the BLR structure. If the ratio of lags is equal to 1, it supports the idea of a narrow ring for the BLR because there is not enough space for the differences in lags to occur that are expected from photoionization models. The radius of the narrow-ring BLR we proposed will influence the radius–luminosity relation (Kaspi et al. 2000; Bentz et al. 2013).

If the major axis of the ellipse is in the plane of the sky (perpendicular to the observer’s LOS, i.e., the major axis orientation angle $\varphi_0 = 90^\circ$ or $270^\circ$; see Figure 2 in Eracleous et al. 1995), the maximum LOS velocity $v_{\text{los}}(\max)$ of an elliptical-ring BLR, corresponding to the red and blue wings of the BEL, will have a time delay that matches the radial distance from the black hole. The mean spectra in Figure 3 and rms spectra in Figure 6 show that the red wing could reach higher velocities than the blue wing (relative to their narrow-line components or the cores of the lines) for the H$\beta$ and H$\alpha$ BELs. Thus, the redward trends presented in Figure 6.1f are qualitatively consistent with the velocity-resolved time lag parameters, BLR inclination angle $i$, and line core. Thus, there might be differences in lags to occur that are expected from photoionization models. The radius of the narrow-ring BLR we proposed will influence the radius–luminosity relation (Kaspi et al. 2000; Bentz et al. 2013).

5. Summary

In this paper, we present photometric (B-band) and spectroscopic monitoring results of CL-AGN NGC 3516 using the Lijiang 2.4 m telescope. This object should be the first CL-AGN that has complete RM data before and after the change in type. From our analysis, we conclude the following results.

1. Our RM observations give a homogeneous and good sampling data set of NGC 3516 during a low-activity phase. Our sampling of RM data in most nights is 2 days, and the average sampling is ~3 days, which are both smaller than the estimated time lags of H$\alpha$ and H$\beta$.

2. The H$\alpha$ lag is $\tau_{\text{H}\alpha} = 7.56^{+2.05}_{-2.10}$ days, and the H$\beta$ lag is $\tau_{\text{H}\beta} = 7.50^{+2.05}_{-0.77}$ days, which are consistent with each other. The Balmer lines may originate from the same region of the BLR. A black hole mass of $M_{\text{BH}} = 2.4^{+0.7}_{-0.3} \times 10^7 M_\odot$ is obtained using an rms H$\beta$ line dispersion of $\sigma_{\text{line}} = 1713.3 \pm 46.7 \, \text{km s}^{-1}$ and $f_\alpha = 5.5$.

3. The time lags increase toward negative velocity for both H$\alpha$ and H$\beta$. The velocity-resolved RM of H$\alpha$ is done for the first time. The line width and velocity-resolved reverberation signature of H$\beta$ in our observations are consistent with the RM results of H$\beta$ in Denney et al. (2010).

4. The CL model based on changes in the accretion rate of the black hole seems to be more favored for NGC 3516.

Object NGC 3516 might be the first CL-AGN that has RM data before and after changing its type. The mystery of the geometry and kinematics of the BLR in NGC 3516 needs further observational research of BELs. A new RM campaign will be run during the next new observation period with the Lijiang 2.4 m telescope.

We are very grateful to the anonymous referee, as well as Dragana Ilic and Luka Popovic, for constructive comments leading to the significant improvement of this paper. We are also grateful for helpful discussions with Yu-bin Li. J.M.B. is grateful for the financial support of the National Natural Science Foundation of China (NSFC; grant No. 11991051). We thank the joint fund of astronomy of the NSFC and the Chinese Academy of Sciences (CAS) under grants No. U1831125 and U1331118. K.X.L. acknowledges financial support from the NSFC (grants No. 11703077 and 12073068) and the Yunnan Province Foundation (202001AT070069). H.T.L. is grateful for the financial support of the CAS Interdisciplinary Innovation Team. We acknowledge the support of the staff of the Lijiang 2.4 m telescope. Funding for the telescope has been provided by the Chinese Academy of Sciences and the People’s Government of Yunnan Province.

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