Supermassive Black Hole and Broad-line Region in NGC 5548: Results from Five-season Reverberation Mapping

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Abstract

NGC 5548 is one of the active galactic nuclei (AGNs) selected for our long-term spectroscopic monitoring with the Lijiang 2.4 m telescope, aiming at investigating the origin and evolution of broad-line regions (BLRs), accurately measuring the mass of supermassive black holes (SMBHs), and understanding the structure and evolution of the AGN. We have performed five-season observations for NGC 5548 with the median sampling interval ranging from 1.25 to 3 days. The light curves of the 5100 Å continuum and broad emission lines are measured after subtracting contamination of the host galaxy starlight. The time lags of the broad He II, He I, H α, and H β lines with respect to the 5100 Å continuum are obtained for each season and their mean time lags over the five seasons are 0.69, 4.66, 4.60, and 8.43 days, respectively. The H γ and H β velocity-resolved lag profiles in the seasons of 2015, 2018, 2019, and 2021 are constructed, from which an “M-shaped” structure is found in 2015 but disappears after 2018. Our five-season reverberation mapping (RM) yields an average virial SMBH mass of \(M_\text{BH}/10^7M_\odot = 14.22\), with a small standard deviation of 1.89. By combining the previous 18 RM campaigns and our five-season campaign for NGC 5548, we find that there exists a time lag of 3.5 yr between the changes in the BLR size and optical luminosity. In addition, we construct the BLR radius–luminosity relation and the virial relation for NGC 5548.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); Supermassive black holes (1663); Reverberation mapping (2019); Time domain astronomy (2109)

Supporting material: machine-readable table

1. Introduction

Reverberation mapping (RM; Blandford & McKee 1982; Peterson 1993) has been widely used in spectroscopic monitoring campaigns to probe the kinematics of broad-line regions (BLRs) and measure the mass of the accreting supermassive black hole (SMBH) in the centers of active galactic nuclei (AGNs; e.g., Peterson et al. 1999; Bentz et al. 2009; Denney et al. 2010; Du et al. 2018b; Hu et al. 2021; Lu et al. 2021a). RM has also been employed in multiband photometric monitoring campaigns to measure accretion disk sizes (e.g., Zhu et al. 2018; Cackett et al. 2020; Guo et al. 2022). Before 2013, RM measurements of ~50 AGNs had been obtained by different spectroscopic monitoring campaigns, from which the canonical radius–luminosity (i.e., \(R_{\text{BLR}}-L_{1500}\)) relation was established (Kaspi et al. 2000; Bentz et al. 2013). However, this RM sample is heterogeneous and mainly consists of sub-Eddington AGNs.

In the last 10 years, based on the different samples, the canonical \(R_{\text{BLR}}-L_{1500}\) relation has been tested for different purposes. The SEAMBH (super-Eddington accreting massive black hole) project focused on spectroscopic RM of high-accretion AGNs. The major finding was that the H β time lags in SEAMBHs are significantly shorter than those in sub-Eddington AGNs (Du et al. 2018b) and the accretion rate is the main driver for the shortened lags (Du & Wang 2019). This finding was subsequently confirmed by the Sloan Digital Sky Survey Reverberation Mapping (SDSS-RM) project, which also found that there are many AGNs located below the canonical \(R_{\text{BLR}}-L_{1500}\) relation (Grier et al. 2017). Hu et al. (2021) and Li et al. (2021) carried out high-cadence spectroscopic monitoring on a number of Palomar-Green quasars and found that some objects have H β time lags shortened by almost 0.3 dex. To investigate the deviations of the \(R_{\text{BLR}}-L_{1500}\) relation, Du et al. (2018a) monitored a sample of AGNs with complex H β line profiles. Lu et al. (2019a) developed a spectroscopic monitoring project for AGNs with disk winds/outflows to investigate whether their BLRs originate from the disk winds or not. Not long after that, Matthews et al. (2020) proposed that the BLR might arise from failed accretion disk winds. New insights into the deviations from the canonical \(R_{\text{BLR}}-L_{1500}\) relation can be gained through enlarging the RM sample size and expanding the dynamic range of the sample’s properties (such as luminosity, SMBH mass, and accretion rate).

On the other hand, investigating BLR evolution in radius and kinematics for individual AGNs along with different luminosity (or accretion) states can provide a new perspective for understanding the deviations from the canonical \(R_{\text{BLR}}-L_{1500}\) relation. This can be implemented through a multiseason RM...
NGC 5548 was therefore the highest-priority target of our long-term spectroscopic monitoring campaign. In 2015, we conducted the first season of observations. Between 2018 and 2021, we continuously performed four seasons of spectroscopic monitoring. Hereafter, we refer to these five seasons as the seasons of 2015, 2018, 2019, 2020, and 2021. The season of 2015 started on 2015 January 7 and ended on 2015 August 1, and the RM measurement of the broad Hβ line as the first result has been reported by Lu et al. (2016). In this work, we not only include this result for the sake of completeness, but also provide other RM measurements including broad Hγ, He II, and He I lines for this season.

The paper is organized as follows. Section 2 describes the observation and data reduction. Section 3 presents the data analysis, including the measurements of light curves, time lags, variability characteristics, and line widths, along with velocity-resolved RM analysis. Section 4 compares our RM results with the previous 18 RM measurements and investigates the BLR radius—luminosity relation, the virial relation, and the secular variation of the BLR in NGC 5548. In Section 5, we estimate the virial SMBH mass of NGC 5548. We end with a summary of our main results in Section 6. Throughout the paper, we use a cosmology with $H_0 = 72 \text{ km} \text{ s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{\Lambda} = 0.7$, and $\Omega_M = 0.3$. 

2. Observation and Data Reduction

After the season of 2015, we continuously monitored NGC 5548 between 2018 and 2021. The spectroscopic observation settings and data reduction were similar to those in Lu et al. (2016) for NGC 5548. The readers are also referred to our previous works on other AGNs Mrk 79, NGC 7469, and Mrk 817 (Lu et al. 2019a, 2021a) for more detailed discussions on the RM experiments.

2.1. Spectroscopy

The spectroscopic observations of NGC 5548 were taken using the Yunnan Faint Object Spectrograph and Camera (YFOSC) mounted on the Lijiang 2.4 m telescope, which is located in the Lijiang observatory of Yunnan Observatories, Chinese Academy of Sciences. YFOSC is equipped with a back-illuminated 2048 × 2048 pixel CCD, with a pixel size of 13.5 µm, a pixel scale of 0′.283 per pixel, and a field of view of 10′ × 10′. It is a versatile instrument for low-resolution spectroscopy and photometry. More information about the Lijiang observatory and telescope is provided in Fan et al. (2015), Wang et al. (2019), Xin et al. (2020), and Lu et al. (2021b).

Following the observations in the season of 2015, we oriented a long slit in the field of view to take spectra of NGC 5548 and a nearby nonvarying comparison star simultaneously. This observation method was described in detail by Maoz et al. (1990) and Kaspi et al. (2000), and widely adopted by recent RM campaigns (e.g., Du et al. 2015; Lu et al. 2021a). The adopted comparison star, SDSS J141758.82+250533.1 (hereafter J1417), has a spectral type of G1 and a V-band magnitude of 13.9. The temperature and radius of the comparison star obtained from our spectral energy distribution fitting and spectral matching are all consistent with the result of Gaia DR3 (Gaia Collaboration et al. 2021). The angular distance between the comparison star and NGC 5548 is 160″. During the seasons of 2018, 2019, 2020, and 2021, J1417 was also monitored by the project All-sky Automated Survey for Supernovae (ASAS-SN; Shappee et al. 2014; Kochanek et al. 2017) with the g-band filter. The photometric data were downloaded from the site6 and used to check the stability of J1417. The resulting g-band light curve is displayed in Figure 1, with a scatter of 0.04 mag. This scatter is comparable to the average photometric error (0.03 mag) of this light curve, implying that J1417’s emission is stable enough that J1417 was selected as the reference star of NGC 5548. Our previous works demonstrated that a comparison star as a reference standard can provide a high-precision flux calibration (Lu et al. 2019a; see also Hu et al. 2015). In some cases, the spectra of the comparison star can be used to calibrate the telluric absorption lines of the target’s spectra (Lu et al. 2021b). In light of the average seeing of the observatory site, we adopted a long slit with a projected width of 2″5. We used Grism 14, which covers the wavelength from ~3600 to 7460 Å and provides a dispersion of 1.8 Å pixel$^{-1}$. The standard neon and helium lamps were used for wavelength calibration.

In total we obtained 315 spectroscopic observations for NGC 5548. In each season, the observations generally spanned January to June. The median sampling intervals of the five seasons range from 1.25 to 3 days. Table 1 shows the observation statistics of the five seasons.

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6 http://www.astronomy.ohio-state.edu/asassn/index.shtml
In order to eliminate other blended components from the spectrum, the scheme of spectral fitting and decomposition is widely used in spectral analysis of AGNs (e.g., Hu et al. 2008; Bian et al. 2010; Dong et al. 2011; Barth et al. 2013, 2015; Guo & Gu 2014; Lu et al. 2019c). Especially in the RM campaign of local AGNs, the host galaxy starlight not only dilutes the variability of the AGN continuum and broad emission lines, but also usually introduces additional random noise due to nightly variations in seeing and target centering within the slit (Lu et al. 2019a; see also Hu et al. 2015). Therefore we prefer to measure the fluxes of the AGN continuum at 5100 Å and broad Hγ, of 28. We randomly select one spectrum per season and display the five spectra in Figure 2 to showcase the spectral quality.

### 3. Data Analysis

#### 3.1. Mean and Rms Spectra

In this section, we calculate the mean and rms (i.e., variable) spectra for the seasons of 2015, 2018, 2019, 2020, and 2021. The mean spectrum is defined as (Peterson et al. 2004)

$$ F_\lambda = \frac{1}{N} \sum_{i=1}^{N} F_i(\lambda), $$

(1)

where $F_i(\lambda)$ is the $i$th spectrum and $N$ is the total number of spectra of each season (see Table 1). The rms spectrum is defined as

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

(2)

First, the narrow-line components of the calibrated spectra are eliminated during the spectral fitting and decomposition (see Section 3.2). Because narrow emission lines usually have apparent variations caused by varying seeing (e.g., [O III] doublets; see Figure 11 of Lu et al. 2019a), this treatment is helpful in singling out the variable spectrum of broad emission lines. Then the calibrated spectra without narrow lines are used to calculate the mean and rms spectra. The results are displayed in Figure 3. We find that the optical radiation of NGC 5548 reaches the maximum in the season of 2020, but its variability is the lowest.

#### 3.2. Light Curves

In order to eliminate other blended components from the spectrum, the scheme of spectral fitting and decomposition is widely used in spectral analysis of AGNs and observations of AGNs. For each calibrated spectrum, the Galactic extinction was corrected using the extinction map of Schlegel et al. (1998). Wavelength shifts usually caused by varying seeing and miscentering were corrected using the [O III] λ5007 line as the wavelength reference. Then we transformed all spectra into the rest frame for subsequent analysis. The average S/N of the spectra at 5100 Å over the five seasons is 77, with a standard deviation of 28. We randomly select one spectrum per season and display the five spectra in Figure 2 to showcase the spectral quality.

### Table 1

| Season | Dates          | Period   | $N$ | $T$ | $T_{\text{median}}$ |
|--------|----------------|----------|-----|-----|---------------------|
| 2015   | 2015 Jan 7–2015 Aug 1 | 206 | 62 | 3.40 | 3.00 |
| 2018   | 2018 Mar 12–2018 Jun 18 | 98  | 40 | 2.51 | 1.25 |
| 2019   | 2018 Nov 28–2019 Jun 20 | 204 | 81 | 2.55 | 2.00 |
| 2020   | 2020 Jan 11–2020 Jun 21 | 163 | 52 | 3.19 | 2.00 |
| 2021   | 2020 Dec 24–2021 Aug 6  | 225 | 80 | 2.84 | 1.75 |

Note. Column (1) is the season. Column (2) gives the dates of spectroscopic monitoring. Columns (3) and (4) are the observation period and the total number of sampling. Columns (5) and (6) are the mean and median spectroscopic sampling intervals.

The two-dimensional spectra were reduced using the standard IRAF procedures, which include bias subtraction, flat-field correction, wavelength calibration, and cosmic-ray elimination. A relatively small extraction window helps to reduce the Poisson noise of the sky background and increase the signal-to-noise ratio (S/N) of the spectra. Therefore, a uniform extraction window of 20 pixels (5″ × 5″) was used and the sky background determined from two adjacent regions (+7″ to +14″ and −7″ to −14″) on both sides of the extraction window was subtracted.

The scientific target NGC 5548 and its comparison star were observed simultaneously in a long slit with the same observing conditions (such as airmass and seeing), so that the spectrum of NGC 5548 can be calibrated accurately by the sensitivity function calculated from the comparison star (see Lu et al. 2019a). Following previous works (e.g., Du et al. 2015; Lu et al. 2016, 2021a), we first generated the fiducial spectrum of the comparison star using data from nights with photometric conditions, and obtained the sensitivity function by comparing the observed spectrum of the comparison star in each exposure to the fiducial spectrum. Then this sensitivity function was applied to calibrate the spectrum of NGC 5548. For each calibrated spectrum, the Galactic extinction was corrected using the extinction map of Schlegel et al. (1998). Wavelength shifts usually caused by varying seeing and miscentering were corrected using the [O III] λ5007 line as the wavelength reference. Then we transformed all spectra into the rest frame for subsequent analysis. The average S/N of the spectra at 5100 Å over the five seasons is 77, with a standard deviation of 28. We randomly select one spectrum per season and display the five spectra in Figure 2 to showcase the spectral quality.
He II, H\(\beta\), and He I lines using spectral fitting and decomposition to isolate the different components of variable spectra.

Following previous works (e.g., Hu et al. 2015; Lu et al. 2021a), we fit and decompose the calibrated spectra (Section 2.2) first, then measure the fluxes of the AGN continuum at 5100 Å and broad emission lines from each best-fitted component. Our fit is based on the MPFIT package (Markwardt 2009), which performs \(\chi^2\) minimization using the Levenberg–Marquardt technique. The fitting window is set to 4200–6110 Å (rest-frame). The spectrum portion at a wavelength longer than \(~6200\) Å is contaminated by the second-order spectrum and therefore is excluded. The following components are included in our fitting: (1) A power law \((f_{\lambda}\propto \lambda^\alpha\), where \(\alpha\) is the spectral index) for the AGN continuum. (2) An iron template from Boroson & Green (1992) for the iron multiplets. In practice, several iron templates have been suggested for fitting the optical or ultraviolet spectrum of AGNs (e.g., Boroson & Green 1992; Véron-Cetty et al. 2004; Kovačević et al. 2010; Park et al. 2022), but NGC 5548 has relatively weak iron multiplets and we find that our fitting is not sensitive to the specific iron template. (3) The host galaxy starlight modeled by the stellar template with an age of 11 Gyr and metallicity of \(Z=0.05\) from Bruzual & Charlot (2003). In the individual and mean spectra of NGC 5548, some stellar absorption lines are present near the wavelength regions of 5876 and 5180 Å, which can give some limitations on the amount of host galaxy starlight. (4) Three Gaussian functions each for the broad H\(\beta\) and H\(\gamma\) lines. (5) Two double Gaussians for the [O III] doublets \(\lambda5007/\lambda4959\). (6) A Gaussian for the narrow H\(\beta\) line. (7) A set of single Gaussians for fitting other narrow emission lines. These components are fitted simultaneously over the fitting window.

As in the previous fitting steps (e.g., Hu et al. 2015; Lu et al. 2021a), we first fit the mean spectrum of each season and then fit the individual spectrum. During the fitting of the mean spectrum, the flux ratio of the [O III] doublets is fixed to the theoretical value of 3; the shift of the weak broad He \(\beta\) line is fixed; the narrow components of the [O III] doublets and all other narrow lines are tied to the same velocity and shift; and the rest of the fitting parameters are allowed to vary. Meanwhile, different host galaxy templates from Bruzual & Charlot (2003) are considered; however, the template with 11 Gyr age and metallicity \(Z=0.05\) gives a rational fit to the stellar absorption lines and the spectral index of the AGN continuum \((\sim\lambda^{-1.5}\) ). Hence this template is adopted throughout. Figures 4 and 5 display the results of spectral fitting and decomposition of the mean spectra of the five seasons. For each season, panel (a) shows the details of the spectral fitting and decomposition, along with the reduced \(\chi^2\). Panel (b) shows the fitting residuals in percentage. Panel (c) shows the net broad H\(\gamma\), He \(\beta\), H\(\beta\), and He I lines, where the best-fitted broad lines are shown as red dashed lines and the total broad-line profiles obtained by subtracting other fitted components are shown as black lines. From this we can inspect the general variations (including the shape of the profile and flux) of the broad lines. During the fitting of the individual spectrum, (1) the spectral index (\(\alpha\)) is fixed to the value fitted from the corresponding

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**Figure 2.** We randomly select one spectrum per season from the calibrated ones (see Section 2.2) to showcase the spectral quality. The Julian date (and calendar date) and S/N at 5100 Å are noted in each panel.

**Figure 3.** Mean and rms spectra of each season calculated from the processed spectra (see Section 2.2); the legend in panel (a) marks the seasons of 2015, 2018, 2019, 2020, and 2021. Just narrow emission lines (such as narrow H\(\gamma\), He \(\beta\), H\(\beta\), [O III], and He I) are subtracted by spectral fitting and decomposition (see Section 3.2) before calculation.
The mean spectrum, since there is some degeneracy between the power-law continuum and the host galaxy (especially for spectra with a low S/N), so decomposing the host galaxy starlight from the individual spectrum benefits from the fixed spectral index (e.g., see Hu et al. 2015). To check the impact of fixed-α and free-α fitting on the results, we make a comparison between the fixed-α and free-α light curves (including cross-correlation analysis) and find that the results are consistent with each other. (2) Narrow lines are also tied to the same velocity and shift. (3) In addition, because the broad He II line is weak, its line width is fixed to the best value obtained from the fitting of the mean spectrum. For each fitting, we calculate the reduced \( \chi^2 \). The reduced \( \chi^2 \) distribution has a median value of 1.21. The net broad lines of the individual spectra are constructed in a similar way to those of the mean spectrum.

The fluxes of the AGN continuum (\( F_{5100} \)) are measured from the best-fitted power-law component at 5100 Å, and the fluxes of the broad H\( \gamma \), H\( \beta \), and He I lines are measured through integration over the best-fitted profile. The light curves of these components along with the uncertainties including Poisson errors and systematic errors are tabulated in Table 2, and partially displayed in Figure 6 (left panels) for the season of 2015, in Figure 7 for the season of 2018, in Figure 8 for the season of 2019, in Figure 9 for the season of 2020, and in Figure 10 for the season of 2021. The smoothing light curves of the AGN continuum at 5100 Å prove that the multicomponent coupled spectra are well decomposed. In the season of 2020, the light curves of the broad H\( \gamma \) and H I lines are not displayed in Figure 9, because we did not detect a credible time lag of both light curves with respect to the varying AGN continuum, owing to the very low cross-correlation coefficient (see Section 3.4).

To check the quality of the spectral calibration, the photometric light curves of NGC 5548 are employed and displayed in the top panels of Figures 6–10. The \( V \)-band light curves displayed in Figure 6 were observed by the Lijiang 2.4 m telescope during the spectroscopic monitoring periods (see also Lu et al. 2016). The \( g \)-band light curves displayed in Figures 7–10 (covering the seasons of 2018, 2019, 2020, and 2021) are compiled from the archives of ASAS-SN (Shappee et al. 2014; Kochanek et al. 2017). By a simple inspection, we can find that the spectroscopic and photometric light curves have very similar variation structures for each season, implying that the spectra are well calibrated. In addition, we measure the fluxes of [O III] \( \lambda 5007 \) (\( F_{\text{O III}} \)) from the best-fitted profile for the whole campaign, yielding a measurement scatter of \( \sim 3.5\% \). Assuming [O III] \( \lambda 5007 \) emission is constant, the scatter of \( F_{\text{O III}} \) can roughly represent the spectroscopic calibration precision of the whole campaign. However, in a previous RM campaign, Lu et al. (2019a) found that the varying observing conditions (e.g., seeing and miscentering) give rise to the apparent variation in flux of the extended components (e.g., \( F_{\text{He II}} \) and \( F_{\text{gal}} \)), see Figures 11 and 12 of Lu et al. 2019a; also see Hu et al. 2015). Consequently, it is certain that our spectroscopic calibration precision for the whole campaign should be better than 3.5%.

### 3.3. Variability Characteristics

We calculate the mean flux \( \langle F \rangle \), the standard deviation \( \sigma_{\text{LC}} \), and the variability amplitude \( F_{\text{var}} \) (Rodríguez-Pascual et al. 1997) and its uncertainty \( \sigma_{\text{var}} \) (Edelson et al. 2002) for all light curves. The variability amplitude \( F_{\text{var}} \) is defined as

\[
F_{\text{var}} = \frac{(\sigma^2 - \Delta^2)^{1/2}}{\langle F \rangle},
\]

where \( \langle F \rangle \) is the mean flux, \( \sigma^2 \) is the variance, and \( \Delta^2 \) is the mean square error. The uncertainty of \( F_{\text{var}} \) is given as

\[
\sigma_{F_{\text{var}}} = \left( \frac{1}{N} \right)^{1/2} \frac{\sigma^2}{\langle F \rangle^2}.
\]

where \( N \) is the total number of epochs of each season. The results are listed in Table 3 and \( F_{\text{var}} \) is also marked in Figures 6–10.

We find that NGC 5548 has the lowest variability in 2020, when the optical radiation reaches its maximum. This is consistent with the finding from the mean and rms spectra (see Section 3.1). This variability characteristic can be explained by the fact that variability amplitude decreases with increasing accretion rate (e.g., Lu et al. 2019b) if the maximum optical radiation corresponds to the maximum accretion rate. In Section 5, we indeed find that NGC 5548 has the highest accretion rate in the season of 2020 (see Table 6).

### 3.4. Time Lag

For each season, the time lags of the broad H\( \gamma \), He II, H\( \beta \), and He I lines with respect to the varying AGN continuum at 5100 Å are calculated using the interpolation CCF (ICCF; Gaskell & Sparke 1986; Gaskell & Peterson 1987). Following Peterson et al. (2004), the centroid of the ICCF above a typical value of 0.8 \( r_{\text{max}} \) is assigned as the time lag, where \( r_{\text{max}} \) is the
maximum cross-correlation coefficient. Monte Carlo simulations of random subset sampling and flux randomization are employed to construct the CCCD, from which the uncertainty of time lags is estimated using the 15.87% and 84.13% quantiles.

For the seasons of 2015, 2018, 2019, 2020, and 2021, the results of cross-correlation analysis are displayed in Figures 6–10, respectively. For each season, (1) the ACF of the AGN continuum light curve is shown in panel (aa); (2) the CCFs between the light curves of the AGN continuum and broad lines (in red) and the corresponding CCCDs (in blue) are shown in panels (ba)–(ea) (hereafter the CCF panels); (3) the rest-frame time lags measured from the above processes ($\tau_{\text{He II}}$, $\tau_{\text{He I}}$, $\tau_{\text{H}\gamma}$, and $\tau_{\text{H}\beta}$) are marked by the vertical dotted lines in the CCF panels, and listed in Table 4; and (4) the maximum cross-correlation coefficients are noted in the CCF panels and Figure 5.

Same as Figure 4, but for the seasons of 2018, 2019, 2020, and 2021.

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**Figure 5.** Same as Figure 4, but for the seasons of 2018, 2019, 2020, and 2021.
The contamination of the host galaxy is eliminated.

The Astrophysical Journal Supplement Series, 263:10 (20pp), 2022 November

Table 2
Light Curves

| JD   | $F_{5100}$ | $F_{\text{He} \Pi}$ | $F_{\text{He} \I}$ | $F_{\gamma}$ | $F_{\text{H} \beta}$ |
|------|------------|---------------------|------------------|--------------|------------------|
|      |            |                     |                  |              |                  |
| 2,457,030.4 | 5.459 ± 0.290 | 0.336 ± 0.149 | 1.348 ± 0.195 | 3.436 ± 0.343 | 8.005 ± 0.241 |
| 2,457,037.5 | 4.962 ± 0.286 | 0.378 ± 0.148 | 1.586 ± 0.195 | 3.795 ± 0.342 | 7.962 ± 0.241 |
| 2,457,043.5 | 5.669 ± 0.327 | 0.538 ± 0.161 | 1.362 ± 0.199 | 3.581 ± 0.351 | 7.885 ± 0.267 |

The season of 2018

| 2,458,190.4 | 4.257 ± 0.190 | 0.295 ± 0.050 | 0.766 ± 0.084 | 1.569 ± 0.114 | 4.873 ± 0.138 |
| 2,458,193.4 | 3.797 ± 0.321 | 0.101 ± 0.084 | 1.060 ± 0.100 | 1.125 ± 0.138 | 4.048 ± 0.151 |
| 2,458,195.3 | 4.106 ± 0.200 | 0.126 ± 0.053 | 0.817 ± 0.085 | 1.190 ± 0.115 | 4.340 ± 0.139 |

The season of 2019

| 2,458,451.4 | 5.159 ± 0.214 | 0.285 ± 0.209 | 2.236 ± 0.092 | 2.504 ± 0.134 | 6.695 ± 0.183 |
| 2,458,455.4 | 6.126 ± 0.233 | 0.867 ± 0.211 | 2.041 ± 0.094 | 2.217 ± 0.137 | 6.918 ± 0.184 |
| 2,458,461.4 | 5.777 ± 0.219 | 1.313 ± 0.210 | 2.505 ± 0.093 | 2.475 ± 0.135 | 6.892 ± 0.183 |

The season of 2020

| 2,458,859.5 | 7.424 ± 0.290 | 1.104 ± 0.245 | 1.948 ± 0.114 | 2.927 ± 0.160 | 8.216 ± 0.214 |
| 2,458,861.5 | 7.554 ± 0.274 | 0.870 ± 0.243 | 2.202 ± 0.113 | 2.722 ± 0.156 | 8.325 ± 0.213 |
| 2,458,863.4 | 8.046 ± 0.284 | 1.219 ± 0.244 | 2.219 ± 0.114 | 3.007 ± 0.158 | 8.512 ± 0.213 |

The season of 2021

| 2,459,208.4 | 5.223 ± 0.384 | 0.820 ± 0.217 | 1.937 ± 0.133 | 2.425 ± 0.192 | 6.987 ± 0.325 |
| 2,459,209.4 | 4.791 ± 0.376 | 0.658 ± 0.216 | 1.675 ± 0.132 | 2.101 ± 0.191 | 6.688 ± 0.324 |
| 2,459,210.5 | 4.543 ± 0.379 | 0.619 ± 0.216 | 1.592 ± 0.132 | 2.083 ± 0.191 | 6.242 ± 0.324 |

Note. The 5100 Å continuum flux is in units of 10^{-15} erg s^{-1} cm^{-2} Å^{-1}, and all broad H\gamma, He II, H\beta, and He I lines are in units of 10^{-13} erg s^{-1} cm^{-2}. The contamination of the host galaxy is eliminated.

This table is available in its entirety in machine-readable form.

also listed in Table 4. For the season of 2020, because the maximum cross-correlation coefficients between the light curves of broad He I (and H\beta) lines and the AGN continuum are far less than 0.5, the time lags are not significant and therefore not listed. The five-season RM gives $\tau_{\text{He} \I}$: $\tau_{\text{He} \II} : \tau_{\text{H} \beta} : 0.69:4.66:4.60:8.43$, which suggests a stratified BLR.

3.5. Line Width

The broad-line width is characterized by either the FWHM or the line dispersion ($\sigma_{\text{line}}$). In RM campaigns, these two parameters are usually calculated from both the mean and rms spectra. It should be noted that the broad Balmer lines of NGC 5548 often have a double-peaked feature (see Li et al. 2016), which also exists throughout our spectroscopic monitoring periods. In the case where the double peaks are distinct, the FWHM of the double-peaked profile should be measured using the method described in Peterson et al. (2004). Specifically, a blue-side peak and a red-side peak are defined on the line profile, and the FWHM is taken as the wavelength separation of the two peaks.

In each season, we first calculate the mean and rms spectra of each broad line using its net broad lines constructed in Section 3.2, and then measure the line widths for each broad line, including the FWHM (mean), $\sigma_{\text{line}}$ (mean), FWHM (rms), and $\sigma_{\text{line}}$ (rms). The broad He I line is excluded because it is too weak for us to measure its line width reliably. We perform Monte Carlo simulations of random subset selection to generate 200 mean and rms spectra for each broad line, from which we construct four line width distributions. Finally, the standard deviations calculated from each distribution are adopted as the uncertainties of the line widths.

In practice, instrument broadening is coupled with varying atmospheric (seeing) broadening. In this work, the average broadening of the broad emission line is estimated by comparing the FWHM of [O III] $\lambda$5007 (410 km s^{-1}) from the high-resolution spectrum (see Whittle 1992) with the average FWHM (807 km s^{-1}) from our whole campaign. This yields instrumental broadening of 695 km s^{-1} (in the FWHM case), corresponding to 295 km s^{-1} (in the $\sigma_{\text{line}}$ case), for a Gaussian model of the [O III] line profile. The broadening-corrected line widths are listed in Table 5, where the broad H\beta line widths from the season of 2015 reported in Lu et al. (2016) are updated. These measurements are used to investigate the virial relation of the BLR in Section 3.6.

3.6. Velocity-resolved RM

Following previous works (e.g., Bentz et al. 2009; Denney et al. 2010; Grier et al. 2013; Du et al. 2016; Lu et al. 2016; Pei et al. 2017), we carry out velocity-resolved RM analysis using the net broad H\gamma and H\beta lines obtained in Section 3.2. For each season, we first calculate the rms spectrum of the net broad lines and select an emission line window from the rms spectrum. Then we divide the broad lines into several uniformly spaced bins within the selected window and measure the velocity-binned light curves by integrating the fluxes in each velocity bin. Finally, we calculate the time lags between the velocity-binned light curves and the AGN continuum at 5100 Å using the same procedures in Section 3.4.
For the seasons of 2015, 2018, 2019, and 2021, the results of velocity-resolved RM analysis are displayed in Figure 11. The top panels (a) show the rms spectra of the net broad Hγ (left) and Hβ (right) lines. The bottom panels (b) show the broad Hβ and Hγ velocity-resolved lag profiles (VRLPs, i.e., velocity-resolved time lags as a function of the line-of-sight velocity, hereafter Hβ VRLPs and Hγ VRLPs). The above velocity-binned light curves are measured from the fitted broad lines. Alternatively, the Hβ and Hγ VRLPs can be measured from the net broad lines constructed by subtracting other blended components from the calibrated spectra. We find that the results from the above approaches are in agreement. For the

Figure 6. Light curves and the results of cross-correlation analysis for the season of 2015. The top panel shows the photometric light curve of NGC 5548 (instrument magnitude of V band) obtained from the Lijiang 2.4 m telescope during the spectroscopic monitoring periods, which is used to check the quality of the spectral calibration. The left panels (a)–(e) are the light curves of the AGN continuum at 5100 Å and the broad He II, He I, Hγ, and Hβ lines; the contamination of the host galaxy on this data has been eliminated by spectral decomposition. The right panels (aa)–(ea) correspond to the autocorrelation function (ACF) of the continuum and the cross-correlation function (CCF) between the broad-line light curves (b)–(e) and the continuum variation (a); the histogram in blue is the cross-correlation centroid distribution (CCCD). We note the variability amplitude \( F_{\text{var}} \) in panels (b)–(e), and the maximum cross-correlation coefficient \( r_{\text{max}} \) in CCF panels (ba)–(ea). The measured time lag is marked by the vertical dotted lines in panels (ba)–(ea). The units of \( F_{5100} \) and the emission lines are \( \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1} \) and \( \text{erg s}^{-1} \text{cm}^{-2} \), respectively.
season of 2020, we do not obtain credible $\text{H}\beta$ and $\text{H}\gamma$ VRLPs due to the very low variability (see Figure 9). The broad helium lines are not considered for the velocity-resolved RM analysis because of very weak fluxes.

Many theoretical models have been used to study the geometry and kinematics of BLRs (e.g., Gaskell 1988; Horne et al. 2004; Gaskell & Goosmann 2013; Grier et al. 2013). A basic notion is that an outflowing BLR would lead to a longer time lag in the red wing than in the blue wing of the line profile (i.e., blue-leads-red). For an inflowing BLR, the situation is just the opposite (i.e., red-leads-blue; e.g., see Figure 14 of Grier et al. 2013). For BLR gas with Keplerian motion (Welsh & Horne 1991), the shortest lag would be in the line wings, and the longest lag would be in the line core if the ionizing source is emitting isotropically, because the gas with a higher velocity is closer to the central SMBH. If the BLR gas is illuminated anisotropically by a central ionizing source, a flat disk or spherical geometry structure of the BLR in Keplerian orbits could give rise to a double-peaked VRLP (Welsh & Horne 1991; Goad & Wanders 1996). Additionally, many works based on different methods have pointed to the scenario where the BLR has a disk-shaped geometry (Wills & Brotherton 1995; Goad & Wanders 1996; McLure & Dunlop 2002; Down et al. 2010). Using the equivalent width of $\text{[O III]}$ as an indicator of
accretion disk inclination, Bisogni et al. (2017b) further confirmed this scenario (see also Risaliti et al. 2011; Bisogni et al. 2017a). Keep these theoretical models of BLR kinematics in mind; below we give a brief description of VRLPs.

In the season of 2015, both the H\textgamma and H\beta VRLPs present an “M”-shaped (or a double-peaked) structure (see Figure 11). This structure was also observed in 2014 (see H\beta VRLP of Pei et al. 2017) and its possible origin has been discussed by Horne et al. (2021). Following theoretical models of BLR kinematics (Welsh & Horne 1991; Goad & Wanders 1996) and suggestions about the BLR geometry (McLure & Dunlop 2002; Risaliti et al. 2011; Bisogni et al. 2017b), we propose that the BLR of NGC 5548 is a virialized flat disk illuminated anisotropically by the central ionizing source during the observation periods. In our previous work of Lu et al. (2016), a simple H\beta VRLP was obtained by dividing the rms spectrum of the broad H\beta line into nine uniformly spaced bins, which presented a nearly symmetric structure, but the lag of the line core bin was shorter than those of adjacent bins. This is actually consistent with the reconstructed H\beta VRLP in this work. In the season of 2018, the H\gamma VRLP presents a distorted “M”-shaped structure whereas the “M”-shaped structure of the H\beta VRLP disappears. In the seasons of 2019 and 2021, the H\gamma and H\beta VRLPs generally present a red-leads-blue trend, but the VRLPs in the red and blue

Figure 8. Same as Figure 7, but for the season of 2019.
wings seemingly have the same time lags. These complex signatures could be caused by a mix of infalling and virialized motions according to the above theoretical models, or by a switch between infalling and virialized as proposed by Xiao et al. (2018). Alternatively, accretion disk winds/outflows with different transparencies could partially shield or obscure the central ionizing source (e.g., Mangham et al. 2017, 2019; Gaskell & Harrington 2018; Dehghanian et al. 2019), leading to anisotropic illuminations onto the BLR and hence giving rise to complex signatures of VRLPs.

In addition, by inspecting Figure 11, we find that the VRLPs change with the seasons. More interestingly, by comparing the VRLPs from the seasons of 2015 and 2018, we find that the changes of $\text{H} \gamma$ VRLPs lag behind those of $\text{H} \beta$ VRLPs, and the reason is that the “M”-shaped structure of $\text{H} \gamma$ and $\text{H} \beta$ VRLPs presented in 2015 changes into a distorted “M”-shaped structure in the $\text{H} \gamma$ VRLPs and disappears in the $\text{H} \beta$ VRLPs in 2018. These findings perhaps indicate a change in the kinematics of the BLR. Using the dynamical modeling approach developed by Pancost et al. (2014) further constraints on the geometry and kinematics of the BLR (see also Pancost et al. 2011; Li et al. 2013, 2018) will be presented in future contributions.

4. Properties of the BLR in NGC 5548

Since 1988, there have been 18 seasons of RM measurements for NGC 5548 from different spectroscopic monitoring campaigns. These campaigns include the AGN Watch project (from 1988 to 2001; see Peterson 1993; Peterson et al. 1998, 1999, 2002), LAMP (The Lick AGN Monitoring Project, in 2008; see Bentz et al. 2009), the AGN STORM Project (Space Telescope and Optical Reverberation Mapping Project, in 2014; see Pei et al. 2017), and three individual RM campaigns that were undertaken mainly by the McGraw-Hill 1.3 m telescope at the MDM Observatory (in 2005, 2007, and 2012; see Bentz et al. 2007; Denney et al. 2010; De Rosa et al. 2018). Our five seasons of RM measurements are based on the long-term spectroscopic monitoring project with the Lijiang 2.4 m telescope. As a result, thus far there have been in total 23 seasons of RM measurements for NGC 5548, making it the most intensively RM-monitored AGN.

In Table 6, we compile the previous RM measurements of NGC 5548 along with our five-season RM results. The annual average AGN continuum flux $F_{5100}$ listed in Table 6 has been corrected for the contamination of the host galaxy, where the values of the first 16 rows are from Kilerci Eser et al. (2015), the 17th row is compiled from De Rosa et al. (2018) and updated by eliminating the host galaxy flux, the 18th row is from Pei et al. (2017), and the last five rows are from this work. We calculate the standard deviations ($\sigma_{line}$) of the AGN continuum light curves for each campaign and list them in Table 6, which are used to estimate the error of the optical luminosity at 5100 Å in Section 4.2. We also list the line dispersion $\sigma_{line}$ measured from the rms spectrum and the time
lag of the broad H$\beta$ line. These quantities are used to calculate the virial SMBH mass in Section 5. Next, based on 23 RM measurements of NGC 5548, we construct the virial relation and the BLR radius—luminosity relation of NGC 5548, and investigate the stability of the BLR.

4.1. The Virial Relation

The BLR lies within the sphere of influence of the central SMBH, and therefore, its kinematics is expected to be dominated by the gravitational potential of the SMBH. This physical property is usually tested through the virial relation, that is, the $V \propto \tau^{-0.5}$ relation, where $V$ and $\tau$ are the line width and time lag of a broad emission line, respectively. For example, the virial relations of the BLRs in Mrk 817 and NGC 7469 were investigated by Lu et al. (2021a) using the archival data. In NGC 5548, the virial relation of the BLR was successively investigated using multiseason RM results by Peterson et al. (2004), Bentz et al. (2007), and Lu et al. (2016). By adding our five-season RM, we update the virial relation in Figure 12. It is possible that the line width measured from the rms spectrum (i.e., the variable spectrum) just represents the projected velocity of the BLR with the broad-line variability (i.e., the variable region), while the line width measured from the mean spectrum actually represents the projected velocity of

![Figure 10](image_url)
the whole BLR with the contributions of the broad-line flux. Therefore, both the FWHM and $\sigma_{\text{line}}$ measured from the mean and rms spectra, that is, FWHM (mean), FWHM (rms), $\sigma_{\text{line}}$ (mean), and $\sigma_{\text{line}}$ (rms), are considered for comparison.

In Figure 12, the dotted--dashed line is the best fit to the relation of $\log$ (FWHM or $\sigma_{\text{line}}$) = $a + b \log \tau$. The yielded slope $b = -0.45 \pm 0.06$ for the FWHM (mean) versus the time lag, $b = -0.45 \pm 0.08$ for the FWHM (rms) versus the time lag, $b = -0.41 \pm 0.05$ for $\sigma_{\text{line}}$ (mean) versus the time lag, and $b = -0.50 \pm 0.07$ for $\sigma_{\text{line}}$ (rms) versus the time lag, all with a mean intrinsic scatter of 0.26 dex. These best-fit results are also marked in the corresponding panels of Figure 12. The measurements from our five-season RM adequately expand the dynamical range of parameters. The dotted lines are fit with a theoretical virial slope of $b = -0.5$ for each case. All slopes obtained from the above virial relations are close to the theoretical virial slope, generally confirming that the whole BLR is bounded by the gravitational potential of the central SMBH.

### 4.3. Stability of the BLR

The central ionizing source illuminates the BLR, which then emits broad emission lines through the photoionization process. Increased continuum radiation caused by a higher accretion rate will enhance the broad-line emissivity of BLR gases at larger distances, leading to the BLR radius (size) increasing and the line width decreasing with continuum luminosity, which is known as the normal breathing effect of BLRs (e.g., Wang et al. 2020). Currently, more than 100 changing-look/ changing-state AGNs have been found and identified (e.g., Shu et al. 2018; Yang et al. 2018; Graham et al. 2020; Liu et al. 2021). Those AGNs underwent extreme (large) variability and sometimes underwent spectral type transitions between type 1 and type 2, and are good candidates for investigating the stability of the BLR in different luminosity (accretion) states.

For NGC 5548, we plot the optical luminosities at 5100 Å ($L_{5100}$) and the BLR radius ($R_{\text{BLR}} = c \tau_{\text{H} \beta}$) as a function of time in panels (a) and (b) of Figure 14, respectively. The maximum difference of the optical luminosity is $\Delta \log L_{5100} [\text{erg s}^{-1}] \approx 0.93$ over the past 30 years, that is, the optical flux of NGC 5548 at high-luminosity states is ~8.2 times larger than that at low-luminosity states. We find that the optical luminosity reduces to the lowest value around 2008, then gradually returns to the highest level around 2020, which also appears around 1998 (see Figure 14). The average BLR radius weighted by the emissivity also shows obvious variations in NGC 5548. The maximum difference of the BLR radius is $\Delta R_{\text{BLR}} \approx 22$ lt-days. Inspecting the secular variations of the optical luminosity and BLR radius shown in Figure 14, we can gather that the BLR radius follows the varying optical luminosity to some degree; however, it seems that the smallest BLR radius occurs around 2012, lagging behind the lowest state of the optical luminosity (around 2008).

Using the same procedure for calculating the time lags of the broad emission lines in Section 3.4, we find that, in NGC 5548, the change of the BLR radius lags behind the varying optical luminosity with a timescale of $\tau_{\text{BLR}}(L_{5100}) = 3.5 \pm 1.8$ yr. The results of cross-correlation analysis (red solid curve) and the corresponding CCCD (blue solid histogram) are shown in panel (ba) of Figure 14, where the measured time lag is marked by a vertical dotted line (in black). By adding our five-season RM results (displayed in symbols of stars), we find this time lag is longer estimated from the standard deviation of $F_{5100}$ (i.e., $\delta F_{5100}$). We fit the results with the relation of $\log c_{\beta \gamma} = a + b \log L_{5100}$, yielding a slope of $b = 0.57 \pm 0.30$. The best-fit relation is displayed with a blue-dotted--dashed line in Figure 13. By adding our five-season RM measurements, this slope is far less than the value of 0.86 reported by Lu et al. (2016) and almost perfectly consistent with the slope (0.53) of the canonical $R_{\text{H} \beta-L_{5100}}$ relation (see Bentz et al. 2013).

For comparison, the canonical $R_{\text{H} \beta-L_{5100}}$ relation with a slope of 0.53 and intrinsic scatter of 0.13 dex (see Bentz et al. 2013) is also plotted in Figure 13. We find that although our RM measurements overall lie 0.13 dex below the canonical relation, the slope lines up with that of the canonical relation. From the 23 RM campaigns of NGC 5548, we calculate a mean H β time lag of 12.3 days with a standard deviation of 6.7 days, and a mean optical luminosity of $1.58 \times 10^{43} \text{erg s}^{-1}$ with a standard deviation of $0.73 \times 10^{43} \text{erg s}^{-1}$. By superimposing the mean values of the time lag and optical luminosity in Figure 13, we find that the location is well consistent with the canonical $R_{\text{H} \beta-L_{5100}}$ relation.

### Table 3

| Season | Light Curves | Mean Flux | $\sigma_{\text{LC}}$ | $F_{\text{var}}$ (%) |
|--------|--------------|-----------|----------------------|----------------------|
| 2020   | $F_{\text{1100}}$ | 4.34 ± 0.30 | 1.05 | 23.28 ± 2.28 |
|       | $F_{\text{H} \alpha}$ | 0.39 ± 0.15 | 0.39 | 93.29 ± 9.87 |
|       | $F_{\text{He I}}$ | 3.12 ± 0.20 | 0.41 | 27.25 ± 1.39 |
|       | $F_{\text{He II}}$ | 3.21 ± 0.57 | 0.67 | 17.96 ± 2.09 |
|       | $F_{\text{He III}}$ | 6.95 ± 0.52 | 0.73 | 9.97 ± 1.01 |

Table 3: Light-curve Statistics

Note. The flux $F_{5100}$ is in units of $10^{-15} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1}$, and the flux of broad emission lines is in units of $10^{-17} \text{erg s}^{-1} \text{cm}^{-2}$. The symbol $\sigma_{\text{LC}}$ denotes the standard deviation of the light curve. The contamination of the host galaxy is eliminated.
than the value of 2.35 yr reported by Lu et al. (2016). Using the line width of broad Hβ, we can estimate the BLR’s dynamical timescale \( t_{\text{BLR}} = c\tau_{\text{He}}/\sigma_{\text{FWHM,He}} \) (see also Lu et al. 2016). The average H\( \beta \) lag (\( \tau_{\text{He}} \sim 12.3 \) days) and average H\( \beta \) line width (\( \sigma_{\text{FWHM,He}} \sim 6000 \text{ km s}^{-1} \)) over the 23 RM campaigns yield a dynamical timescale of \( \sim 2.1 \) yr. Thus, \( \tau_{(\text{He},L_{5100})} \) is slightly longer than the BLR’s dynamical timescale in NGC 5548.

Interestingly, after extreme damping in the optical luminosity, the change of the BLR radius in NGC 5548 seemingly follows the optical luminosity in an even tighter fashion, which is more clearly seen in our five-season RM measurements (as if \( \tau_{(\text{He},L_{5100})} \sim 0 \); see the symbols of stars in Figure 14). To make a further investigation, a subset of the BLR radius and optical luminosity after 1997 (marked by the vertical dashed lines in panels (a) and (b) of Figure 14) are selected to recompute the time lag. The results of cross-correlation analysis (red dashed curve) and the corresponding CCCD (blue dashed histogram) are overplotted in panel (ba) of Figure 14, where the measured time lag is marked by a vertical dotted line (in gray). This yields a relatively longer time lag of \( \tau_{(\text{He},L_{5100})} = 4.6^{+1.3}_{-1.7} \) yr. Currently, the difference between \( \tau_{(\text{He},L_{5100})} \) and \( \tau_{(\text{He},L_{5100})} \) is statistically insignificant, but whether the BLR response timescale varies with the illumination history is unclear. Therefore, continuous RM campaigns with high-quality data are needed to understand the evolution of the BLR radius and optical luminosity in NGC 5548.

The relation between the line width of broad H\( \beta \) and the optical luminosity for NGC 5548 is investigated in Figure 15. This figure shows that the line dispersion of broad H\( \beta \) from the 23 RM campaigns does not globally correlate with the optical luminosity, which is not consistent with Wang et al. (2020)’s finding from the SDSS-RM sample that the line width of broad H\( \beta \) decreases with increasing optical luminosity (i.e., normal breathing). In contrast, the line dispersion of broad H\( \beta \) from our five-season RM (shown as “x”) is inversely correlated with the optical luminosity. In Figure 15, a dotted line with a slope of \( -0.5 \) is plotted over the data to guide the eye. The explanations for these discrepancies are unclear and more investigations are needed.

In addition, extreme variability including that of the AGN continuum and broad emission lines is the most significant observation feature of changing-look/changing-state AGNs. The mainstream view is that a dramatic change in accretion rate triggers the changing-state process of AGNs (e.g., Sheng et al. 2017). But a deeper question is what mechanism is responsible for the dramatic change in accretion rate and whether the dramatic change occurs in the BLR during or before the changing state. If the BLR supplies material to the accretion
Figure 11. The results of velocity-resolved RM analysis for the seasons of 2015, 2018, 2019, and 2021. For each season, panel (a) shows the rms spectrum of broad Hγ (left) or Hβ (right), and panel (b) shows the centroid time lags as a function of velocity in the line of sight. The vertical dotted lines are the edges of the velocity bins. The Hγ and Hβ VRLPs are plotted in the same coordinate ranges in the direction of the velocity axis. All maximum cross-correlation coefficients between the velocity-binned light curves and the varying AGN continuum at 5100 Å are larger than 0.5. Note that the broad-line velocity binning is below the instrumental resolution of \(\sim 695\) km s\(^{-1}\), and thus the measurements are not independent.
Note. The AGN continuum flux at 5100 Å ($F_{5100}$) and its standard deviation ($\sigma_{\text{5100}}$) are in units of erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$, which are used to calculate the optical luminosity at 5100 Å and its uncertainty. The line dispersion ($\sigma_{\text{line}}$) measured from the rms spectrum of the broad H$\beta$ line and the H$\beta$ time lag are used to calculate the virial product and virial SMBH mass ($M_{\text{BH}}$). Other line widths including the FWHM and $\sigma_{\text{line}}$ measured from the mean and rms spectra are referred to in Table 4 of Lu et al. (2016), De Rosa et al. (2018), and Pei et al. (2017). The dimensionless accretion rate $\dot{M}$ is estimated using the optical luminosity and SMBH mass.

References. (1) Kilerci Eser et al. (2015), (2) Collin et al. (2006), (3) Bentz et al. (2013), (4) Bentz et al. (2007), (5) Denney et al. (2010), (6) Bentz et al. (2009), (7) De Rosa et al. (2018), (8) Pei et al. (2017), (9) Lu et al. (2016), (10) this work.

5. Black Hole Mass and Accretion Rate

The examination of the virial relation in Section 4.1 shows that, on a 30 yr timescale, the BLR of NGC 5548 is dominated by the gravitational potential of the central SMBH. In this case, the SMBH mass can be well estimated by the virial equation:

$$M_{\text{BH}} = \frac{f \tau_{\text{H}/3} V^2}{G},$$

where $\tau_{\text{H}/3}$ is the H$\beta$ time lag, $c$ is the speed of light, $c\tau_{\text{H}/3}$ is the BLR radius, $G$ is the gravitational constant, the BLR velocity or line width $V$ is either the FWHM or line dispersion ($\sigma_{\text{line}}$) of the broad emission lines measured from the mean or rms spectrum, and $f$ is a dimensionless virial factor that incorporates the unknown geometry, kinematics, and inclination of the BLR. Ho & Kim (2014) found that the uncertainty of the virial factor $f$ can be reduced after considering the bulge type (including classical bulge and pseudobulge) of the host galaxy. For example, in the case of line dispersion $\sigma_{\text{line}}$ measured from the rms spectrum, $f = 6.3 \pm 1.5$ for classical bulges.

In light of the factors that (1) the line width measurement from the rms spectrum eliminates contamination of the constant components, (2) the line dispersion $\sigma_{\text{line}}$ produces less biased mass measurement than the FWHM (see Peterson 2011), and (3) NGC 5548 hosts a classical bulge (Ho & Kim 2014), we calculate the SMBH masses for our five-season RM campaigns and the previous RM campaigns in a uniform way, using the line dispersion $\sigma_{\text{line}}$ of broad H$\beta$ from the rms spectrum and $f = 6.3 \pm 1.5$. We also calculate the virial products defined as $c\tau_{\text{H}/3}/\sigma_{\text{line}}/G$ for all the RM campaigns. The results are listed in Table 6, where the last five rows list the results from our five-season RM campaigns. The SMBH masses derived from the previous 18 campaigns, ranging between 2.07 and 13.82 in units of $10^7 M_{\odot}$, are relatively diverse. However, the SMBH
masses derived from our five-season RM campaigns, ranging between 12.45 and 16.97 in units of $10^7 M_\odot$, are almost consistent with each other. Our five-season RM yields an average virial SMBH mass of $14.22 \times 10^7 M_\odot$, with a small standard deviation of $1.89 \times 10^7 M_\odot$. The stellar velocity dispersion of the classical bulge in NGC 5548 is $\sigma_\ast = 195 \pm 13$ km s$^{-1}$ (Woo et al. 2010). According to the $M_{BH}-\sigma_\ast$ relation of Kormendy & Ho (2013), we obtained $M_{BH,\ast} = (27.50 \pm 8.80) \times 10^7 M_\odot$ in Lu et al. (2016). This SMBH mass is remarkably consistent with our measurements within uncertainties.

The dimensionless accretion rate is defined as (Du et al. 2015)

$$\dot{M} = \frac{\dot{M}_{BH}}{L_{Edd}} \left( \frac{L_{5100}}{L_{Edd}} \right)^{3/2} M_\odot^{-2},$$

where $\dot{M}_{BH}$ is the mass accretion rate, $L_{Edd} = 1.5 \times 10^{38} (M_{BH}/M_\odot) \text{ erg s}^{-1}$ is the Eddington luminosity, $i$ is the inclination of the accretion disk, $\cos i = 0.75$ is adopted (which represents a mean disk inclination for a type 1 AGN), $L_{5100} = L_{5100}/10^{44}$ erg s$^{-1}$ is the optical luminosity at 5100 Å,
and $M_7 = M_{\text{BH}}/10^7 M_\odot$ is the SMBH mass. With the optical luminosity and virial SMBH mass, the dimensionless accretion rates for each season are estimated and listed in Table 6. The 23 RM campaigns yield an average accretion rate of $\langle \dot{\mathcal{M}} \rangle = 0.034$ with a standard deviation of 0.034, indicating that NGC 5548 is overall in a sub-Eddington accretion state. During our five-season RM campaigns, NGC 5548 has the maximum accretion rate of $\dot{\mathcal{M}} = 0.025$ in the season of 2020 (see Table 6).

6. Summary

We began a long-term spectroscopic monitoring project for NGC 5548 in 2015, which aimed to investigate its BLR properties and accurately measure the virial SMBH mass. This project was undertaken with the Lijiang 2.4 m telescope. We performed five-season RM observations between 2015 and 2021, with the median sampling interval ranging from 1.25 to 3 days. In this work, we conducted the basic measurements and carried out velocity-resolved RM analysis. Spectral fitting and decomposition processes were employed during spectral analysis to improve the RM measurements. For the seasons of 2015, 2018, 2019, 2020, and 2021, we obtained the following main results.

1. We measured the light curves of the AGN continuum at 5100 Å and the broad He II, He I, Hγ, and Hβ lines. The time lags of these broad-line light curves with respect to the AGN continuum at 5100 Å were measured, ranging from 0 to 10 days, and their mean lags over the five seasons are $\langle \tau_{\text{He II}} \rangle = 0.69$ days, $\langle \tau_{\text{He I}} \rangle = 4.66$ days, $\langle \tau_{\gamma} \rangle = 4.60$ days, and $\langle \tau_{\beta} \rangle = 8.43$ days. This demonstrates that the BLR in NGC 5548 obeys radial ionization stratification.

2. We constructed the Hγ and Hβ VRLPs for the seasons of 2015, 2018, 2019, and 2021, from which we found that both the Hγ and Hβ VRLPs exist as an “M”-shaped structure in the season of 2015 (also in 2014; see Pei et al. 2017), but this structure disappears after 2018. Infalling and Keplerian motion could dominate the kinematics of the BLR in NGC 5548, and the two kinds of motion might coexist, leading to the complex BLR kinematics. Alternatively, accretion disk winds/outflows with different transparencies partially shield the BLR, which may also give rise to complex signatures of VRLPs. We found that the Hγ and Hβ VRLPs vary with the seasons, implying an evolution in the kinematics of the BLR. Continuous velocity-resolved RM experiments are needed to figure out the decisive explanation.

3. After eliminating other blended components and correcting for instrumental broadening, we measured the FWHM and σ_{line} of broad Hβ, Hγ, and He I from the mean and rms spectra for each season. Using the line dispersion of Hβ from the rms spectrum, the Hβ time lag, and the dimensionless virial factor ($f_{\text{HLR}} = 6.3$) of the classical bulge, we calculated the virial SMBH mass of NGC 5548 from our five seasons of observations, which ranges from $12.45 \times 10^7 M_\odot$ to $16.97 \times 10^7 M_\odot$. The average virial SMBH mass is $M_7/10^7 M_\odot = 14.22$, with a small standard deviation of 1.89.

By combining the previous 18 RM campaigns and our five-season campaign for NGC 5548, we obtained the following results and remarks.

1. We derived the $R_{\text{HLR}}-L_{5100}$ relation of NGC 5548 with a slope of 0.57. The mean values of $c \times \tau_{\text{He II}}$ and $L_{5100}$ over the 23 campaigns are consistent with the canonical $R_{\text{HLR}}-L_{5100}$ relation. The measurements from our five-season RM overall lie 0.13 dex below the canonical relation, but the resulting slope is consistent with the canonical relation (Bentz et al. 2013). Our results actually increase the weight below the canonical relation, making the slope of NGC 5548’s individual $R_{\text{HLR}}-L_{5100}$ relation close to 0.5.

2. We obtained the virial relation of the BLR in NGC 5548 and found that the whole BLR is bounded by the SMBH’s gravitation well. The virial SMBH masses updated from the previous 18 RM campaigns range from 2.07 to 13.82 in units of $10^7 M_\odot$, which are relatively diverse. As a comparison, the virial SMBH masses from our five-season RM range from 12.45 to 16.97 in units of $10^7 M_\odot$ with a much smaller scatter.

3. We found that the change of the BLR radius lags behind the change of the optical luminosity with a timescale of $3.5^{+2.5}_{-1.8}$ yr. This timescale is relatively larger than the value (2.35 yr) reported by Lu et al. (2016), and longer than the BLR’s dynamical timescale of $\sim 2.1$ yr. However, after extreme damping in the optical luminosity, the BLR radius seemingly shows a normal breathing effect (i.e., the BLR radius increases with increasing optical luminosity), which is more clearly seen in our five-season RM measurements. To make a further investigation, a subset of the BLR radius and optical luminosity measured after 1997 was selected to recalculate the time lag, which
yields a longer timescale of $4.6^{\pm 1.7}_{1.3}$ yr. Currently, the difference between both timescales is statistically insignificant, and whether the BLR response timescale varies with the illumination history is unclear. In addition, we found that the line dispersion of broad H$\beta$ from the 23 RM campaigns is not globally correlated with the optical luminosity, while the line dispersion from our five-season RM is well inversely correlated with the optical luminosity.

It is crucial to investigate the reasons for the above differences so as to better understand the structure and evolution of the BLR. We will continue to monitor NGC 5548 for this purpose. The RM results of our long-term spectroscopic monitoring project for other AGNs (e.g., Mrk 1018, Mrk 590, and SDSS J153636.22+044127.0) will be presented in future contributions.

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