Measuring cosmological distances of active galactic nuclei from spectroastrometry and reverberation mapping: application to 3C 273

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ABSTRACT

Using spectroastrometry, the GRAVITY at The Very Large Telescope Interferometry successfully revealed the structure and kinematics of the broad-line region (BLR) of 3C 273 with an unprecedented high spatial resolution. Spectroastrometry measures the BLR angular sizes of active galactic nuclei (AGNs) whereas reverberation mapping (RM) of AGNs independently provides their linear sizes. In this paper, we suggest a new scheme making a joint analysis of observations of spectroastrometry and RM of AGNs to measure their cosmological distances. We apply this scheme to 3C 273 observed by both the GRAVITY and RM campaign, and find its angular distance of $551.5^{+97.3}_{-78.7}$ Mpc (with an averaged accuracy of 15%). The advantages of the scheme rest on the feasibility of directly measuring cosmological distances without the invoking of otherwise calibrations through known cosmic ladders. Moreover, we can easily repeat measurements of selected AGNs to efficiently reduce the statistic and possible systematic measurement uncertainties. With RM campaigns, a GRAVITY-sample with a reasonable size ($\sim 25$ AGNs) will provide accurate measurements of distances of the AGNs and hence a new way of measuring the Hubble constant with high precision ($\lesssim 3\%$) for cosmology.

Keywords: cosmology – distance – optical interferometry

1. INTRODUCTION

Distances of celestial objects are a fundamental parameter in cosmology (Peacock 1999; Freedman & Madore 2010; De Grijs & Cartwright 2011; Weinberg et al. 2013). Popular measurements of cosmological distances are usually achieved by using Cepheid variable stars and type Ia supernovae (SNIa), giving rise to a great discovery of accelerated expansion of the Universe (Riess et al. 1998; Perlmutter et al. 1999). In the era of precision cosmology, it urgently needs better measurements of cosmological distances to observationally test the recent increasing tension (up to $\sim 4.4\sigma$) of the local Hubble constant measured from Cepheids and cosmic microwave background (Freedman 2017; Riess et al. 2019).

Thanks are given to the team of the GRAVITY at the Very Large Telescope Interferometry (VLTI) for its unprecedented high spatial resolution through spectroastrometry (Gravity Collaboration et al. 2017), which was successfully applied to the first quasar for spatial resolution of its broad-line region (BLR) (Gravity Collaboration et al. 2018). This makes it feasible to directly measure angular sizes ($\xi_{BLR}$) of the BLRs in AGNs. In the meanwhile, fortunately, reverberation mapping (RM) of AGNs (Blandford & McKee 1982) has been known to reliably measure linear sizes ($R_{BLR}$) of the BLRs for many years through detecting delays of broad emission lines as response to the varying continuum from light curves (LCs) of RM campaigns (see a classical review of Peterson 1993). A joint analysis of spectroastrometry and RM observations of AGNs is expected to directly provide absolute angular distances from $D_A = R_{BLR}/\xi_{BLR}$ to observers, avoiding calibrations with known cosmic ladders.

In this paper, we propose a new scheme of measuring AGN distances from such a joint analysis of the GRAVITY and RM observations. The scheme is described in §2 and applied to 3C 273 with both observations of the GRAVITY and RM campaign in §3. Discussions are provided in §4, and conclusions in the last section.

2. A NEW SCHEME FOR COSMIC DISTANCES

2.1. The BLR and reverberation in AGNs

AGNs and quasars are radiating with huge powers and their spectra are prominently characterized by broad emission lines from optical to ultraviolet bands (see an early review of Osterbrock & Mathews 1986; Osterbrock 1989; Ho 2008). The standard
Figure 1. Structure and kinematics of simplest BLR in AGNs, which are characterized by a flatten disk with opening angle of $\Theta_{BLR}$. Clouds are presumed to be optically thin and are orbiting around the central black hole with Keplerian velocity. The blue and red clouds are approaching and receding to observers, respectively. Covering factor of the BLR clouds is about 10%, representing a fraction of reprocessing energy released by accretion onto black holes. A remote observer has an inclination of $i_0$ located in the $O-YZ$ plane.

model is accretion onto supermassive black holes (SMBHs) located in galactic centers (Rees 1984). Emission lines from the gas ionized by photons released from the accretion are broaden by great potential of the SMBHs and appear with a full-width-half-maximum (FWHM) spanning from $\sim 10^3$ to a few $10^4$km s$^{-1}$. This is the well-known paradigm of the BLR. As a natural consequence of photoionization, the emission lines will follow the variations of the continuum, but with a delay of $\tau_{BLR}$. Considering that the recombination timescale $\tau_{rec} \approx (n_e/\alpha_B)^{-1} \approx 0.1 \times 10^7$ hr is much shorter than $\tau_{BLR}$, the delays of the emission lines represent the linear dimension of the emission line regions, where $n_{10} = n_e/10^4$cm$^{-3}$ is electron density of clouds and $\alpha_B$ is the case B recombination coefficient (Osterbrock 1989). This delayed response is known as reverberation of the BLR (see a detailed explanation in Peterson 1993). RM observations measure LCs of broad emission lines and continuum, and then allow us to analyze temporal relation between the lines and the continuum for the BLR geometry and kinematics (Peterson 1993). In practice, $\tau_{BLR}$ can be easily measured from the simple cross-correlation function, however, exact meanings of $\tau_{BLR}$ can be specified through modeling BLR for its linear sizes.

The understanding of BLRs has been advanced much after great efforts of RM campaigns for about 70 AGNs during the last more than three decades (Peterson et al. 1998; Kaspi et al. 2000; Bentz et al. 2013; Du et al. 2018). It has been found that, except for optical Fe II-strong AGNs (Du et al. 2018), BLR sizes follow a well-known $R - L$ relation (Bentz et al. 2013; Du et al. 2014) agreeing with the photoionization as major mechanism. These Fe II-strong AGNs are mostly super-Eddington objects powered by slim accretion disks (Abramowicz et al. 1988; Wang et al. 2014b), breaking the assumption of isotropic ionizing sources made in the explanation of H$\beta$ line reverberation. Fe II-weak AGNs are powered by the standard accretion disks and can be well approximated by isotropic sources. Secondly, a disk-like geometry has been generally found in many broad-line Seyfert 1 galaxies from velocity-resolved delay map (Grier et al. 2013; Bentz et al. 2013; Lu et al. 2016; Du et al. 2016b; Xiao et al. 2018), even in some narrow-line Seyfert 1 galaxies (Du et al. 2016b). Moreover, there is growing evidence for Keplerian rotation of the BLR clouds through multiple campaigns of several AGNs, such as, NGC 5548, NGC 3783, 3C 390.3 and NGC 7469 (Peterson et al. 2004, hereafter), stratified radial structure of the BLR according to the ionization energy of ions in NGC 5548 (Peterson & Wandel 2000), or vertical structure of the BLR (see Fig. 24 in Kollatschny et al. 2014). As the zero-order approximation of the present scheme, we simply assume that the BLR clouds are orbiting around the central black hole in this paper.

In a brief summary, RM campaigns can efficiently measure linear sizes of the BLRs of sub-Eddington AGNs. Moreover, AGNs with symmetric H$\beta$ profiles can be described by a simple BLR model, which is characterized by a flatten disk with circular Keplerian rotation. Besides the geometry and kinematics, we still need to specify spatial distributions of BLR clouds to model the observed LCs of continuum and broad emission lines.

2.2. BLR model

Many efforts have been made to model the RM data of $\sim 10$ mapped AGNs in details through Markov Chain Monte Carlo (MCMC) simulations since Pancoast et al. (2011), offering empirical formulations of spatial distributions of the BLR clouds for the present joint analysis. We follow the approach described in Pancoast et al. (2014), but we take the simplest version of the model by keeping the necessary numbers of parameters. The half-opening angle of the BLR is $\theta_{opn}$, and the inclination angle is...
Here the bold letters are vectors. Supposing the surface distribution of the regions, we have

\[ u = B / \lambda \]

where \( u \) is the spatial frequency, \( \epsilon \) is the photocentre of the source at wavelength \( \lambda \), \( \lambda_i \) is the wavelength of a reference channel. Here the bold letters are vectors. Supposing the surface distribution of the regions, we have

\[ \epsilon(\lambda) = \frac{\int \alpha \mathcal{O}(\alpha, \lambda) \, d^2\alpha}{\int \mathcal{O}(\alpha, \lambda) \, d^2\alpha}, \]

where \( \mathcal{O}(\alpha, \lambda) \) is the optical depth, which is used...
where $O(\alpha, \lambda) = O_\ell + O_\ell$ is the surface brightness distribution of the source contributed by the BLR and continuum regions, respectively, $\alpha$ is the angular displacement on the celestial sphere. Given geometry and kinematics of a BLR, its $O_\ell$ can be calculated for one broad emission line with the observed central wavelength $\lambda_{\text{cen}}$ through

$$O_\ell = \int \frac{\Xi_\ell F_\ell}{4\pi r^2} f(r, V) \delta(\alpha - \alpha') \delta(\lambda - \lambda') \, d^3 r \, d^3 V,$$  \hspace{1cm} (5)$$

where $\lambda' = \lambda_{\text{cen}} \gamma_0 (1 + V \cdot n_{\text{obs}}/c) (1 - R_S/r)^{-1/2}$ including the gravitational shifts, $\gamma_0 = (1 - V^2/c^2)^{-1/2}$ is the Lorentz factor, $\alpha' = |r - (r \cdot n_{\text{obs}}) n_{\text{obs}}|/D_\Lambda$, $r$ is the displacement to the central BH, $\Xi_\ell$ is the reprocessing coefficient at position $r$ and $f(r, V)$ is the velocity distribution of the clouds at that point, respectively, $F_\ell$ is ionizing fluxes received by an observer, $n_{\text{obs}}$ is the unit vector pointing from the observer to the source and $D_\Lambda$ is the angular size distance of the AGN. Introducing the fraction of the emission line to total ($\ell_\lambda$), we have

$$\epsilon(\lambda) = \ell_\lambda \epsilon_\ell(\lambda),$$  \hspace{1cm} (6)$$

where

$$\epsilon_\ell(\lambda) = \frac{\int r O_\ell \, d^2 \alpha}{\int O_\ell \, d^2 \alpha}, \quad \ell_\lambda = \frac{F_\ell(\lambda)}{F_{\text{tot}}(\lambda)}, \quad F_\ell(\lambda) = \int O_\ell \, d^2 \alpha, \quad F_{\text{tot}}(\lambda) = F_\ell(\lambda) + F_\ell(\lambda).$$

Inserting Eq.(6), (5) and (4) into (3), we can obtain phase curves. Since $B/\lambda \sim 100m/2.2\mu m$ and $\epsilon \sim 100\mu as$, $\phi_\epsilon$-amplitudes are expected to be at a level of a few degrees and to spatially resolve compact objects.

2.4. Reverberation mapping

Detailed descriptions of one-dimensional modeling of the BLR are given by Li et al. (2013, 2018). For reader’s convenience, we briefly summarize all the necessary formulations. In order to interpolate and extrapolate the sampled LC of the varying continuum, we use the damped random walk (DRW) model to describe the continuum variations (Kelly et al. 2009; Zu et al. 2013). For a time series of $y$, the measured data can be expressed by $y = s + n + E\hat{q}$, where $s$ is the variation signal that is described by the DRW model, $n$ is the measurement errors, $q$ is the mean values of the series, and $E$ is a vector with all unity elements. The covariance function of the DRW model is given by

$$S(t_1, t_2) = \sigma_d^2 \exp \left(-\frac{|t_1 - t_2|}{\tau_d}\right),$$  \hspace{1cm} (7)$$

for any two points at times $t_1$ and $t_2$ (Kelly et al. 2009), where $\sigma_d$ is the long-term standard deviation of the variations and $\tau_d$ is the typical timescale of the variation. Supposing that both $s$ and $n$ are Gaussian and unrelated (see details of Li et al. 2013, 2018), the best estimate of $q$ is given by

$$\hat{q} = E^T C^{-1} y,$$

where the superscript “$T$” denotes the transposition, $C = S + N$, $S$ and $N$ are the covariance matrix of the signal $s$ and noise. Using the Bayes’ theorem, we can recover the damped random walk process to determine the best values of $\sigma_d$ and $\tau_d$ for a given set of the series. The most probable estimate of the variation signal $s$ at any time $t_*$ is given by

$$\hat{s} = S^T C^{-1} (y - E\hat{q}).$$  \hspace{1cm} (9)$$

A typical realization for the continuum LC is (Li et al. 2018)

$$f_c = (u_s + \hat{s}) + E(u_q - \hat{q}),$$  \hspace{1cm} (10)$$

where $u_s$ follows a Gaussian process with a zero mean and covariance of $Q = [S^{-1} + N^{-1}]^{-1}$, and $u_q$ follows a Gaussian process with a zero mean and covariance of $(E^T C^{-1} E)^{-1}$. We treat $u_s$ and $u_q$ as free parameters, which are further constrained by the LC data of the emission line.

Given the BLR geometry and kinematics in Section 2.2, we can easily calculate the response of the entire BLR to the varying continuum in order to fit the observed data. The time-dependent fluxes of broad emission line can be calculated by summing up the reprocessing emissions from all the clouds in the BLR as

$$f_\ell(t) = \int dr \, dt' \frac{\Xi_\ell f_\ell(t')} {4\pi r^2} n(r) \delta (t' - t + \tau),$$  \hspace{1cm} (11)$$

where $\tau = (r - r \cdot n_{\text{obs}})/c$, $\Xi_\ell$ is the reprocessing coefficient and $n(r)$ is the number density of the clouds. Given the BLR model, Eqs. (10,11) are used to fit the observed LCs denoted as the 1D-RM analysis.
2.5. Joint analysis

The goal of a fully joint analysis is to obtain the posterior probability distribution of the model parameters using the combined data from RM campaign and GRAVITY observations. Suppose that the probability distribution for the measurement errors of LCs, profiles and differential phase curves are Gaussian and uncorrelated. The joint likelihood function can be written as

\[
P(\mathcal{D}|\Theta) = \prod_{i=1}^{N_{\text{dat}}} \frac{1}{\sqrt{2\pi}\sigma_i} \exp\left\{-\frac{[f_{\ell,\text{obs}} - f_{\ell,\text{mod}}(f_{\ell,\text{obs}};\Theta)]^2}{2\sigma_i^2}\right\} \times \prod_{i=1}^{N_C} \prod_{j=1}^{N_{\lambda}} \frac{1}{\sqrt{2\pi}\sigma_{\phi,ij}} \exp\left\{-\frac{[\phi_{\ell,\text{obs}} - \phi_{\ell,\text{mod}}(\Theta)]^2}{2\sigma_{\phi,ij}^2}\right\} \times \prod_{j=1}^{N_{\lambda}} \frac{1}{\sqrt{2\pi}\sigma_{\phi,ij}} \exp\left\{-\frac{[F_{\ell,\text{obs}} - F_{\ell,\text{mod}}(\Theta)]^2}{2\sigma_{\phi,ij}^2}\right\},
\]

(12)

where \( \mathcal{D} \) represents the measured data, \( \Theta \) represents all the model parameters, \( f_{\ell,\text{obs}} \) is the observed continuum data, \( f_{\ell,\text{mod}} \), \( \phi_{\ell,\text{obs}} \), and \( \phi_{\ell,\text{mod}} \) are the observed line flux, line profile, and interferometric phase of the emission line with measurement uncertainties \( \sigma_{\ell}, \sigma_{\phi,ij}, \) and \( \sigma_{F} \), respectively, and \( (f_{\ell,\text{mod}}, F_{\ell,\text{mod}}, \phi_{\ell,\text{mod}}) \) are the corresponding predicted values from the BLR model. Table 1 lists all the parameters used in the modeling. Notes on the roles of individual parameters in the GRAVITY and RM data are also given, showing necessity of the joint analysis of the GRAVITY and RM data. In light of Bayes’ theorem, the posterior probability distribution for \( \Theta \) is given by

\[
P(\Theta|\mathcal{D}) = \frac{P(\Theta)P(\mathcal{D}|\Theta)}{P(\mathcal{D})},
\]

(13)

where \( P(\Theta) \) is the prior distribution of the model parameter and \( P(\mathcal{D}) \) is a normalization factor.

We generate mock data to test the present scheme. Error bars of the GRAVITY phase curves are set to be \( \sim 25\% \) and RM data at the level of the 3C 273 campaign. We find that the generated parameters of the model from the mock data are in well agreement with the input within accuracy of 10\%. This demonstrates that the present joint analysis is feasible for distances and black hole mass of AGNs. We omit the details for mock data, but we show an application to 3C 273 below.

3. APPLICATION TO 3C 273

3.1. Observations and data

3C 273 is the first quasar discovered by Schmidt (1963). Its redshift is \( z = 0.158339 \) (from NASA Extragalactic Database) and K-band magnitude \( K \approx 10.0 \), which is very suitable to observe through the GRAVITY (Gravity Collaboration et al. 2018). The GRAVITY has successfully measured the differential phase curves (\( \phi_\alpha \)) of 3C 273 in July 2017, January, March and May 2018 (Gravity Collaboration et al. 2018, hereafter). Spectral resolution of the GRAVITY is about \( \lambda/\Delta\lambda \approx 500 \). The GRAVITY data are from Gravity Collaboration et al. (2018). We apply the present scheme described above to fit the 24 baselines of the GRAVITY differential phase curves and the Paschen \( \alpha \) profiles. The broad Paschen \( \alpha \) line regions are found to be \( R_{\text{BLR}} = 145 \pm 35 \) ldt with help of a presumed angular distance of 550 Mpc. However, the angular distance is regarded as a free parameter in the joint analysis of the GRAVITY and RM data.

A 10yr RM campaign of 3C 273 has been carried out by Zhang et al. (2019) through joint observations of the Bok 2.3m telescope in Steward Observatory (SO), University of Arizona, and the Lijiang 2.4m telescope in Yunnan Observatory, Chinese Academy of Sciences. Details of the campaign are described by Zhang et al. (2019), but we briefly summarize here. The campaign of the Bok 2.3m telescope started from March 2008 and the Lijiang 2.4m telescope from December 2016 to May 2018. We totally have 296 spectra with a mean cadence of 7.4 days for the entire campaign. Details of observations and data reduction can be found in Zhang et al. (2019).

We note that the varying continuum has a long trending of decreases, but H\( \beta \) LC does not have the same trending, as shown in Fig. 3 (Zhang et al. 2019) (see also the Appendix in this paper). Thus the broad H\( \beta \) line has no proper reverberation of the long trend, see details in the Appendix. It has been suggested that the de-trending is an efficient way to improve the RM analysis of long-term secular variability of continuum (Welsh 1999; Peterson et al. 2004). De-trending is often necessary to introduce in RM analysis. We take a linear form of de-trending effects as \( f_c \propto k_c(t - t_0) \) for the continuum LCs, where \( k_c \) is determined by the joint analysis.

3.2. Fittings

We take the priors of the BLR parameters in sufficiently wide ranges in order to guarantee the unique solutions of the model. Ranges of parameters are provided in Table 1. The priors of \( \mathcal{F}, \beta, \theta_\text{opt}, t_0 \) and PA are uniform over the given intervals, while
Figure 2. Fittings of the DPCs from the 24 baseline interferometric data. The first rows are Paα line profiles, but they are almost identical in the four observation periods. The DPCs generate the angular sizes of the BLR.

those of $R_{\text{BLR}}$, $M_*$ and $D_A$ are uniform in log scale. The cosmological dilation factor of $(1 + z)$ has been included in generating LC to fit observations of 3C 273 in the BLR modeling. The posterior is sampled using the Diffusive Nested Sampling (e.g., Brewer & Foreman-Mackey 2018) and we obtain a total of 5000 samples for all model parameters.

In Appendix, we provide evidence for that the varying continuum before 2012 is significantly contaminated by non-thermal emissions from the relativistic jet. The contaminations make the joint analysis of the whole RM data unsatisfactory. We will quantitatively eliminate contaminations of the jet in a future paper of Li et al. (in preparation) and carry out the results separately.

3.3. Results: distances

Considering the contaminations of the continuum, we only take the RM data after 2012 and the differential phase curves into the joint analysis. The best-fittings to the data from GRAVITY observation and RM campaign are shown in Fig. 2 and 3, respectively. The one- and two-dimensional projection of probability density distributions of eight model parameters are given by
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Figure 3. One-dimensional fitting of the reverberation mapping data since 2012 (avoiding contaminations of the relativistic jet, see details in Appendix) through the BLR model. Fluxes of Hβ line are in units of $10^{-13}$ erg s$^{-1}$ cm$^{-2}$, and $F_V$ is in unit of $10^{-14}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ converted from V-band magnitudes. This yields the linear sizes of the BLR. Scattering points of the Hβ LC around beginning of 2012, 2013 significantly contributes to $\chi^2 = 1.61$, which is relatively larger than that of fitting the GRAVITY data.

Fig. 4. The median value and 1σ error bar for each parameter are also given there and listed in Table 1. The reduced $\chi^2$ is 1.26 for GRAVITY data, and 1.61 of the RM data\(^1\), respectively. We found $k_c = (7.9 \pm 0.2) \times 10^{-5}$ in units of erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ days$^{-1}$ from the joint fitting. Some of parameters have the similar values with those of Gravity Collaboration et al. (2018) within error bars, or different within reasonable ranges.

The present joint analysis generates angular and linear sizes of the BLR for the angular distances

$$D_\Lambda = 551.5^{+97.3}_{-78.7} \text{ Mpc},$$

implying a relative statistical error bar of $\Delta D_\Lambda / D_\Lambda \approx 16\%$ on averaged. This is a very encouraging accuracy for the first joint analysis of the GRAVITY and the RM campaign. The most prominent advantage of this analysis is direct measurement without calibrations of cosmic ladders. We demonstrate that the combination of the GRAVITY and RM observations is a feasible and powerful tool of measuring AGN distances. Considering the future improvements of the GRAVITY (e.g., GRAVITY+ as the next generation of the GRAVITY), the error bars of distances measured by the present scheme can be significantly reduced.

4. DISCUSSIONS

4.1. Quasars as cosmological probes

Quasars are the most luminous and long-lived celestial objects in the Universe. After discovery, they were instantly suggested for cosmological distances (Sandage 1965; Hoyle 1966; Longair & Scheuer 1967; Baldwin 1977). However, these efforts were not successful because of poorly understanding of quasar physics. Recently, interests of applications of quasars to cosmology have arisen again by selecting special individuals or populations.

\(^1\) The $\chi^2$ of RM data is a little bit higher than normal. We note that this could be caused by a couple of points significantly deviate from the model. Except for these points, the $\chi^2$ will be greatly reduced. Considering the major goals of the present paper, we keep this fitting with the $\chi^2 = 1.61$ as resultant fittings.
Direct measurements of distances through very long base interferometry (VLBI) observations of water masers in NGC 4258 ($z \approx 0.0015$) (Humphreys et al. 2013), and torus diameters through direct imaging observations of NGC 4151 ($z \approx 0.0033$) (Hönig et al. 2014) have been suggested, but these methods are limited either by the rare sources of water masers or the long period of NIR monitoring campaigns. Super-Eddington accreting massive black holes (SEAMBHs over much wider ranges of redshifts) from their saturated luminosity (Wang et al. 2013, 2014a; Marziani & Sulentic 2014; Du et al. 2018) were suggested and show potential application to high-$z$ Universe (Cai et al. 2018). Moreover, following relations have been also suggested for cosmology, such as the well-known $R - L$ relation of sub-Eddington AGNs (Watson et al. 2011; Czerny et al. 2013; King et al. 2015) or its improved version (Martínez-Aldama et al. 2019), X-ray variance versus luminosity (La Franca et al. 2014), and the non-linear UV versus X-ray luminosity relation (Risaliti & Lusso 2019). Quasars as cosmological objects seem to be a very promising tool to probe the Universe, but much work needs to be done for a robust probe (see a review of Marziani et al. 2019).

We would like to point out that all the mentioned methods need calibrations of cosmic ladders except for the way of the VLBI water maser and NIR RM. The application of $R - L$ relation to cosmology has been initiated (e.g. King et al. 2015; Czerny

Figure 4. Contours of parameters from the joint fittings of differential phase curves and Hβ reverberation data. The best values of parameters are given on the tops of panels. Error bars are quoted at 1σ level, which are given by parameter’s distributions.
et al. 2019; Hoormann et al. 2019), but high-$z$ quasars are hard to measured for emission line lags because of the dilation factor of $(1 + z)$. SEAMBHs as a new kind of cosmic ladders can be in principle extended to high-$z$ quasars (Negrete et al. 2018; Martínez-Aldama et al. 2018) from the local scaling relation (Du et al. 2016a).

The present scheme of joint analysis of the GRAVITY and RM observations provides a direct method without calibration of known ladders. Future GRAVITY observations of low-$z$ SEAMBHs will provide an efficient way of calibrating SEAMBHs to high-$z$ Universe. It is then expected for us to use AGNs for accurate measurements of distances from low-$z$ to high-$z$ Universe.

### 4.2. BLR model

Measurements of both the GRAVITY and the RM data depend on the BLR model, namely the geometrically thick disk with Keplerian rotation. Complicated structures and kinematics of the BLRs are possible, however, we should note that they can be observationally tested. In principle, the systematic errors can be independently estimated from RM campaigns as argued below.

#### 4.2.1. Differences with the previous

As shown in Table 1 and Fig. 4, the present results from the joint analysis are significantly different from the previous, however they seem to be reasonable. As shown by Eq.(3), the phase curves are more sensitive to the BLR information projected to the baseline direction. RM of broad H$\beta$ line mainly delivers its information along the line of sight. We expect different sensitivities of the GRAVITY and RM data on model parameters. Independent analysis may result in different values of the model parameters, but the joint analysis generate more robust results for both databases. On the other hand, the cross correlation analysis generates a lag of the H$\beta$ response, but its exact meanings are quite ambiguous even its error bars are very small. Currently, the lags of broad emission lines are popularly explained as an emissivity-averaged radius of the BLR, however, the geometric radius remains open without specifications of a physical model. Once given the BLR geometry and kinematics, a joint analysis of the GRAVITY and RM data generates the BLR parameters of the best fittings for both independent datasets (the GRAVITY and RM data) simultaneously. For 3C 273, we would understand the situations, but it needs observations of more targets for a better understanding. Mock data will help understand this issue in a forthcoming paper.

Moreover, the current analysis of the GRAVITY+1D-RM should be extended to that of the GRAVITY+2D-RM, which includes information of variations of H$\beta$ profiles. The 2D-RM analysis will provide more information of the realistic BLR and improve accuracies of the current measurements.

#### 4.2.2. Geometry and kinematics

The characterized BLR model of a geometrically thick disk with Keplerian rotation can be observationally tested by repeating campaigns (for any times in principle). Disk-like geometry of the BLR can be examined by the velocity-resolved delays (the 2D transfer functions), showing distinguished shapes of the transfer functions from other geometries, such as inflows or outflows (Welsh & Horne 1991). Symmetric profiles of broad emission lines form from axis-symmetric disks. Moreover, kinematics can be tested by repeated campaigns of the targets. A Keplerian rotation will show a simple relation of $\tau_{\text{BLR}} \propto V_{\text{FWHM}}^{-2}$. It is thus feasible to estimate uncertainties of BLR geometry and kinematics as the systematic error bars of the model.

We should note that the GRAVITY measured the Pa$\alpha$ line region whereas the 10-yr RM campaign did the H$\beta$ line. A fully self-consistent scheme should employ a same line. However, RM campaign of near infrared emission lines are much harder than H$\beta$ line. Fortunately, statistics show that Pa$\alpha$ line shares the same region with H$\beta$ line (Landt et al. submitted).

#### 4.2.3. BLR variations

There is growing evidence that BLRs are variable with luminosities, such as in NGC 5548 (e.g., Lu et al. 2016). Since the GRAVITY observations only take a few hours, which is much shorter than length of RM campaigns (usually a few months). Therefore the GRAVITY may detect BLR at different epochs from the RM campaigns. This may be one origin of the systematic uncertainties. The RM campaign of 3C 273 is as long as 10yr whereas the GRAVITY observations just took a snaps over one hour or so in the last two years. The timescale of BLR variation is roughly given by $t_{\text{BLR}} \approx R_{\text{BLR}}/V_{\text{FWHM}} = 42\tau_{150}V_{3000}^{-1}$ yr, where $\tau_{150} = \tau/150\text{days}$ and $V_{3000} = V_{\text{FWHM}}/3000\text{km s}^{-1}$. In order to avoid BLR variations, we should do RM campaign in the same period of the GRAVITY observations.

#### 4.2.4. Degrees of ordered motion

Spectroastrometry measures the mean centers of $\lambda$-photons from the BLR and thus depends on the angular momentum distributions, namely on the degree ($R_0$) of ordered motion of the BLR clouds (Stern et al. 2015; Rakshit et al. 2015; Songsheng et al. 2019). $R_0 = 1$ is presumed in the GRAVITY observations of 3C 273 (Gravity Collaboration et al. 2018). In principle, $R_0$ should
be treated as a free parameter in fitting the DPCs of the GRAVITY data, but it strongly degenerate with the BLR size. \( R_0 \) could be estimated from polarized spectra and position angles risen by scatters of hot electrons in the mid-plane (Smith et al. 2005; Songsheng & Wang 2018). It is beyond the scope of the present paper to build up the relation between \( R_0 \) and position angles of the polarized spectra, but we will carry it out separately.

4.2.5. Error budgets

We briefly discuss the error sources of the joint measurements. First, the degree of disordered motion could be the largest uncertainty of the present analysis. This involves formation of the BLR, either from disk winds (e.g., Czerny & Hryniewicz 2011) or tidally captured clumps of torus (Wang et al. 2017). It is expect to test \( R_0 \) through polarized spectra. Secondly, non-Keplerian kinematics and non-disk BLR (or taking different form of Eq. 1) are another sources of systematic errors. Fortunately, this can be done by repeating RM campaigns of individual AGNs to demonstrate the sources through direct test of the relation between \( \tau_{H\beta} - \text{FWHM} \) and velocity-resolved delay relation \( (\tau_{H\beta} - V) \) for the BLR geometry, where \( V \) is the velocity bin. Actually, the systematic errors can be efficiently alleviated through selecting targets with symmetric profiles of broad emission lines.

Selection of radial and angular distributions of BLR clouds in the model is another source of systematical errors. Detailed discussions on this issue are beyond the scope of this paper, but we will investigate it through mock data in a future paper. Finally, on observational side, there are a few key valleys and peaks for determinations of model parameters, however, they are in season gaps, such as, second half years of 2012, 2015, 2016, 2017. Accuracies of model parameters are then affected in the joint analysis. Actually, we continue the campaign with a goal of getting better valleys and peaks in next a few years.

4.3. Local Hubble Constant

We can measure the local Hubble constant (LHC) \( H_0 \) through the present scheme after determination of cosmological distances of AGN sample. Using the results of 3C 273 from the joint analysis, we have

\[
H_0 = 71.5^{+12.7}_{-10.2} \pm 1.5 \text{ km s}^{-1} \text{ Mpc}^{-1},
\]

(15)

given \( \Omega_M = 0.315 \) and \( \Omega_{\Lambda} = 0.685 \) from the Planck measurements of CMB (Planck Collaboration et al. 2018). Considering that the current accuracy of distance measurements of one individual target is \( \Delta D_A/D_A \sim 0.16 \) (this is mainly controlled by the GRAVITY and can be improved significantly), we have uncertainties of \( H_0 \) given by \( \Delta H_0/H_0 = \Delta D_A/D_A \approx 3 N_{25}^{1/2} \) per cent, where \( N_{25} = N/25 \) is number of the AGN sample. This accuracy is slightly worse than that of individual Cepheids (e.g., Riess et al. 2019). The campaigns for 25 AGNs can be feasibly done by one or two dedicated 2m-class telescopes within one year whereas it only takes about \( \sim 10 \) days for the GRAVITY to perform observations of 25 AGNs. The GRAVITY can observe Paschen-\( \alpha \), Bracket-\( \gamma \) lines of the targets with different redshifts (e.g., GRAVITY \(^+\)). Such a median campaign is feasible in practice. A 4-year project of the GRAVITY observations and RM campaign of 100 AGNs is feasible to provide a \( H_0 \) with an accuracy if about 1.5 per cent, which will be the highest accuracy.

Targets selected for LHC should focus on AGNs, which have smooth, symmetric profiles in order to reduce systematic errors. Moreover, it is well-known that variation amplitudes of AGNs anti-correlate with accretion rates (Kelly et al. 2009; Lu et al. 2019). The Fe\( ii \)-weak AGNs should be selected for targets with large variable amplitudes for convenient RM campaigns.

Advantages of the present scheme are obvious. First, distance measurements are direct without calibration of cosmic ladders for \( H_0 \), which are different from applications of Cepheid variable stars and type Ia supernovae to \( H_0 \). Second, the targets can be easily selected from existing AGN catalogs. They can be repeatedly measured because of their long life time, allowing us to test and reduce systematic error bars of the results. Third, the targets spatially distribute over all sky so that we have opportunities to test the anisotropy of \( H_0 \), i.e., the anisotropy of accelerated expansion (Peebles 1993).

5. CONCLUSIONS

Reverberation of emission lines delivers the linear sizes of the emitting regions and spectra-astrometry probes their angular sizes. In this paper, we suggest a new scheme to determine angular distances of active galactic nuclei (AGNs) through joint analysis of observational data from the GRAVITY at The Very Large Telescope Interferometry and reverberation mapping campaigns. We illustrate the feasibilities of the present scheme through an application to the first quasar 3C 273, which is the only one observed by both the GRV AITY and a 10-yr RM campaign. We find that 3C 273 is at an angular distance of \( 515.5^{+78.7}_{-78.7} \) Mpc with an averaged error of \( \sim 15\% \). This error bar can be significantly reduced by improved GRAVITY observations in future. Moreover, a joint analysis of the 2-dimensional RM and the phase curves will also improve the current model for a more realistic measurement (to be carried out separately).
Future RM-GRAVITY observations of $\sim 25$ AGNs will allow us to determine the local Hubble constant $H_0$ with a high precision ($\lesssim 3\%$). Such a campaign can be performed in one year. The present $H_0$-tension will be tested effectively for cosmology.

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Figure 5. The *Fermi* γ-ray LC and comparison with V-band observed for 10 yrs. ASAS-SN: All-Sky Automated Survey for Supernovae (see http://www.astronomy.ohio-state.edu/assassin/index.shtml).

APPENDIX

3C 273 is a blazar with prominent big blue bump (Walter et al. 1994) and a powerful relativistic jet (see an extensive review of Courvoisier 1998). The varying continuum from optical to UV will be contaminated in some degrees by the jet sometimes. In our joint analysis of the whole RM data, we found that fitting is hardly good due to the contaminations. In this Appendix, we show two pieces of evidence for contaminations of the observed continuum.

A. CONTAMINATIONS

In Fig. 6, we show the γ-rays monitored by the LAT of the *Fermi* satellite\(^2\). The ≥ 30GeV emission must be generated by the most inner part of the jet (e.g., Blandford & Levinson 1995), and thus contaminations could be tested by γ-rays. The *Fermi* monitoring campaign is continuous without season gaps so that we can test the long-term trend. We generate the γ-ray LC according to the *Fermi* user’s Guider, see also the γ-ray LC in Meyer et al. (2019). It is obvious that there is a giant γ-ray flare in the second half year of 2009 and first months of 2010, and the flare has a long tail lasting to the end of 2011. It is not the goal of the present paper to make a detailed comparison between the γ-ray and V-band LCs, but it is quite obvious that the flare significantly contributes to the observed optical continuum. It is also clear that the response of the broad H\(\beta\) line to the optical continuum is quite weak. This can be seen more clear in Appendix B.

B. WEAK RESPONSE OF BROAD H\(\beta\) LINE

Detailed analysis of RM data can be found by cross correlation functions in Zhang et al. (2019). De-trended continuum LC can be obtained by subtracting \(f_c \propto k_0(t - t_0)\). Following Zhang et al. (2019), we found \(k_0 = 8.0 \times 10^{-5}\) from a linear regression of the 5100Å LCs since 2009. This is shown by Fig. 6a and 6b. Zhang et al. (2019) obtained a lag of \(\tau_{BLR} = 146 \pm 8\) days by analyzing the de-trended continuum and H\(\beta\) LCs. Fig. 6c shows the entire LC of H\(\beta\) line. We shifted the H\(\beta\) LC backward by the \((1 + z)\tau_{BLR}\) and compare with the de-trended continuum through multiplying \(F_{H\beta}\) a reasonable factor in Fig. 6d. It is very clear that the response of H\(\beta\) is quite weak before 2012. One of the plausible reasons is that both the optical and UV continuum are contaminated by the jet located outside the BLR, but the BLR has no response to this continuum component. Another reason might be due to non-linear response of the BLR clouds as described in the MCMC approach (Pancoast et al. 2011; Li et al. 2013). The present model only focuses on the linear response at the zero-order of the model.

\(^2\) https://fermi.gsfc.nasa.gov/ssc/data/access/
Figure 6. The whole LC of continuum and Hβ line since 2009. Panel a: 5100Å LC (in units of $10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$), b: de-trended 5100Å, c: Hβ and d Hβ versus de-trended 5100Å. In panel d, the Hβ shifted LC is multiplied by a factor for a simple comparison. It is obvious that Hβ line between 2009-2012 has poor response to the varying continuum.