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POLARIZATION IN LINES—A NEW METHOD FOR MEASURING BLACK HOLE MASSES IN ACTIVE GALAXIES

Victor L. Afanasiev[1] and Luka Č. Popović[2,3,4]
[1] A Special Astrophysical Observatory of the Russian Academy of Sciences, Nizhnij Arkhyz, Karachaevo-Cherkesia 369167, Russia; vafan@sao.ru
[2] Astronomical Observatory Belgrade, Volgina 7, 11060 Belgrade, Serbia; lpopovic@aob.rs
[3] Department of Astronomy, Faculty of Mathematics, University of Belgrade, Studentski Trg 16, 11000 Belgrade, Serbia
[4] Isaac Newton Institute of Chile, Yugoslavia Branch-Chile, Belgrade, Serbia
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ABSTRACT

Measuring the masses of galactic supermassive black holes (SMBHs) is an important task since they correlate with the host galaxy properties and play an important role in the evolution of galaxies. Here, we present a new method for measuring SMBH masses using the polarization of the broad lines emitted from active galactic nuclei (AGNs). We performed spectropolarimetric observations of nine AGNs and found that this method gives measured masses that are in a good agreement with reverberation measurements. An advantage of this method is that it can be used to measure the masses of SMBHs in a consistent way at different cosmological epochs.

Key words: line: profiles – polarization – quasars: supermassive black holes

1. INTRODUCTION

It is widely accepted that all massive galaxies host supermassive central black holes (SMBHs) ranging in mass from fewer than one million solar masses to many billions of solar masses. The masses of SMBHs are known to correlate with the bulge properties of their host galaxies (Heckman & Kauffmann 2011; Kormendy & Ho 2013), and understanding this is important for understanding the evolution of galaxies (see Heckman & Best 2014). Therefore, measuring SMBH masses at different cosmological epochs is an important task in astrophysics today. There are several methods (direct and indirect) that have been used to measure black hole masses in the center of galaxies (see Peterson 2014), where direct methods, especially reverberation, can be used for measuring black hole masses of low-redshift quasars. However, measuring SMBH masses from a single-epoch observed spectrum of quasars is still in a developmental stage (Peterson 2014).

Here, we show how the polarization of the broad lines emitted from active galactic nuclei (AGNs) can be used to measure the masses of supermassive black holes. We tested the method (see Afanasiev et al. 2014) for a sample of nine AGNs that have been observed with the 6 m telescope of the Special Astrophysical Observatory of the Russian Academy of Science (SAO RAS). Contrary to reverberation, the method only needs one epoch of observation of an AGN.

The paper is organized as follows: in Section 2, we describe the method, and in Section 3, we outline our observations and obtained results.

2. METHOD

We make use of the fact that polarized light in broad AGN lines can, in some cases, be interpreted as being caused by scattering in the inner part of a dusty torus (so-called equatorial polarization; for more details, see Smith et al. 2005; Afanasiev et al. 2014). The broad lines are emitted from the broad-line region (BLR) that is close to the SMBH; consequently, one can expect near-Keplerian motion of the emission gas in the BLR (Gaskell 2009). A rotating, Keplerian line-emitting BLR surrounded by a co-planar scattering region produces a polarized broad line, where the position angle (PA) of polarization averaged across line profile is aligned with the projected BLR rotation axis (Smith et al. 2005), and the stratified velocity field of Keplerian-like motion in the BLR produces a characteristic change of the PA across the line profile (see Figure 1, upper panel). This gives a nearly equal but opposite maximum in the blue and red wings of the line (Smith et al. 2005; Afanasiev et al. 2014).

Let us consider a simple model as shown in Figure 1 (lower panel), considering an approximation of a single scattering element from the torus. The polarization angle across the line profile[5], $\Delta\varphi(\lambda) = \varphi_L(\lambda) - \varphi_C(\lambda)$, depends on the velocity field in the BLR (Smith et al. 2005). For Keplerian motion, the velocity depends on the distance of the emitting gas from the SMBH as $V_i \sim R_i^{-1/2}$, and it also depends on the polarization angle as $V_i \sim \tan(\Delta\varphi_i)^{-1/2}$ (see Figure 1, lower panel). The relationship between velocities and polarization angles across the line profile is thus (Afanasiev et al. 2014)

$$\log\left(\frac{V_i}{c}\right) = a - 0.5 \cdot \log\left(\tan\left(\Delta\varphi_i\right)\right), \tag{1}$$

where c is the velocity of light. The constant a directly depends on the black hole mass as

$$a = 0.5 \log\left(\frac{GM_{\rm BH}\cos^2(\theta)}{c^2 R_{\rm sc}}\right), \tag{2}$$

where G is the gravitational constant, $R_{\rm sc}$ is the distance of the scattering region from the central black hole, and θ is the angle between the disk and the plane of the equatorial scattering region (see Figure 1). Since the BLR is expected to be nearly co-planar with the torus, one can take $\theta \sim 0$ as a good approximation. The effect of a wide (or a non-co-planar) torus (e.g., $\theta \sim 10$–$20°$) can give an error in black hole mass (see Equation (2); $M_{\rm BH}(\theta = 0)/M_{\rm BH}(\theta \neq 0) = \cos^2(\theta)$) measurement around 5%–10%. There also can be partial obscuration of the BLR, but it is connected with the orientation of the system with respect to the line of sight. In principle, one cannot expect

[5] Where $\varphi_L(\lambda)$ is the PA in the line and $\varphi_C(\lambda)$ is the PA in the continuum.

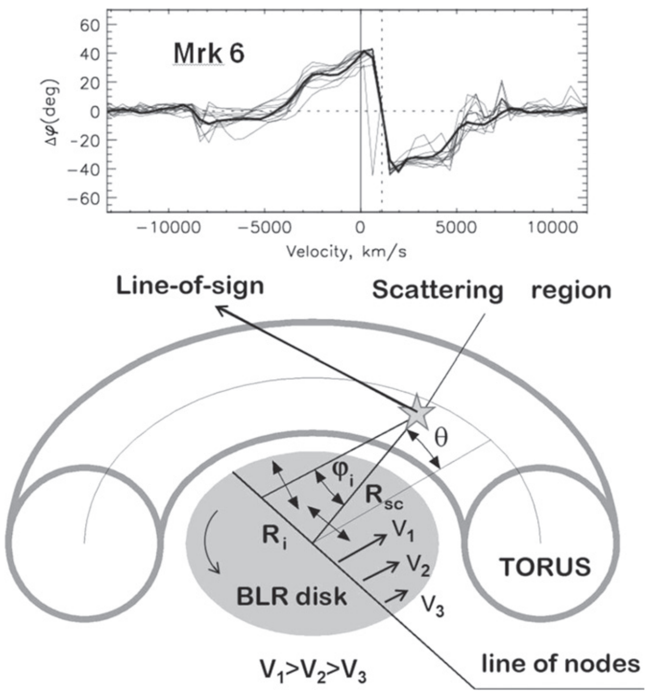

Figure 1. Our assumed scattering geometry is indicated in the lower panel of the figure, and the observed dependence of polarization angle ($\Delta\varphi$) vs. velocities in the Hα line profile of Mrk 6 is shown in the upper panel of the figure (see Afanasiev et al. 2014).

a high contribution of the equatorial scattering of the line light in the edge-on or face-on orientation of the system, i.e., the equatorial scattering can be expected in the systems with an inclination between 20° and 70°. On the other hand, the relation between velocities and $\Delta\varphi$ does not depend on the inclination of the system since the Keplerian disk emits nearly edge-on orientated line light to the scattering region and the relation between log (V_i) and log (tan ($\Delta\varphi_i$)) is close to 0.5 (as it shows a preliminary simulation by STOKES code; R. Goosmann 2014, private communication).

Note here that in the case where a full scattering ring is taken into account (not a single scattering region as we assumed here), scattered emission will occur at various polarization angles and there will not be a one-to-one relation between R and ϕ. However, in the case of an inclined system (torus + Keplerian disk), the dominant scattered light is coming from one side of the torus, while scattered light for the opposite side is blocked, and the single scattering region approximation can be used (R. Goosmann 2014, private communication). More detailed discussion of the model, numerical simulations, and exploration of the BLR and scattering region parameters using polarization in broad lines will be given in an extensive forthcoming paper (V. L. Afanasiev et al. 2015, in preparation).

To measure the black hole mass using Equation (2), it is necessary to estimate $R_{\rm sc}$. This is expected to be the inner radius of the torus (Smith et al. 2005). There are two possible ways to find $R_{\rm sc}$. The first is to use the empirical relationship between the inner torus radius and the luminosity of the AGN (Kishimoto et al. 2011; Koshida et al. 2014), and the second is to estimate it directly from infrared observations (Kishimoto et al. 2011; Koshida et al. 2014).

3. OBSERVATIONS AND RESULTS

To test the method here, we have selected a sample of nine AGNs (see Table 1), for which estimates of the inner radius of their tori are given in the literature (Kishimoto et al. 2011; Koshida et al. 2014). We have obtained spectropolarimetry of the AGN with the 6 m telescope of SAO RAS using a modified version of the SCORPIO spectrograph (for more details, see Afanasiev & Moiseev 2011). The reduction of observed data and corrections for the interstellar polarization is described in Afanasiev et al. (2014) and will not be repeated here. The observed AGNs and their basic data are given in Table 1.

The observed shapes of $\Delta\varphi$ and $\frac{V_i}{c}$ for two of the objects, 3C273 and NGC 4051, are shown in Figure 2. It can be seen in Figure 2 that the polarization angle shapes indicate Keplerian-like motion (Figure 2, upper panel) and that Equation (1) fits the observed points relatively well except for the low-velocity part (see Figure 2, lower panel), where emitting gas is close to the torus and possible Keplerian motion is not dominant. Therefore, we did not consider points with $V_i \sim 0$ since they are close to the inner radius of the torus and this simple scattering geometry does not work, and then we took $V_{\rm min}$ for $\Delta\varphi < 45°$.

In Table 1, we give estimates of $R_{\rm sc}$ with corresponding literature references (columns 4 and 5, respectively; see Kishimoto et al. 2011; Koshida et al. 2014), estimates for coefficient a (see Equation (2)), and our black hole masses (columns 6 and 7, respectively). We have also compiled reverberation-mapping estimates of the black hole masses from the literature (column 8 in Table 1; see Peterson et al. 2004;

Table 1
List of Observed AGNs with Basic Data and Measured Black Hole Masses Using the Polarization in Broad Line (Column 7) Compared with Ones Measured by the Reverberation Method (Column 8)

Object	Type	z	$R_{\rm SC}$ (pc)	References	$-a$	log ($M_{\rm POL}$)($M_\odot$)	log ($M_{\rm REV}$)($M_\odot$)	References
Mkn 6	1.5	0.0188	0.185	1	2.19 ± 0.21	8.18 ± 0.42	8.13 ± 0.04	3
3C273	1.0	0.1583	0.809	1	2.19 ± 0.13	8.85 ± 0.27	8.95 ± 0.09	4
Akn 120	1.0	0.0323	0.380	1, 2	2.44 ± 0.18	8.02 ± 0.36	8.18 ± 0.06	4
NGC 4051	1.0	0.0024	0.032	1, 2	2.90 ± 0.09	6.23 ± 0.18	6.24 ± 0.13	4
NGC 4151	1.5	0.0033	0.037	1, 2	2.34 ± 0.13	7.21 ± 0.27	7.12 ± 0.05	4
Mkn 335	1.2	0.0258	0.119	2	2.48 ± 0.07	7.44 ± 0.14	7.40 ± 0.05	3
NGC 3227	1.5	0.0039	0.021	1, 2	2.32 ± 0.21	7.01 ± 0.42	6.88 ± 0.10	5
NGC 5548	1.5	0.0172	0.096	2	2.30 ± 0.27	7.70 ± 0.33	7.82 ± 0.02	6
Mkn 817	1.5	0.0315	0.151	2	2.42 ± 0.11	7.67 ± 0.21	7.64 ± 0.11	5

References. The estimates for $R_{\rm SC}$ are taken from (1) Kishimoto et al. (2011) and (2) Koshida et al. (2014). The reverberation measurements of black hole masses are taken from (3) Grier et al. (2012), (4) Peterson et al. (2004), (5) Denney et al. (2010), and (6) Bentz et al. (2007).

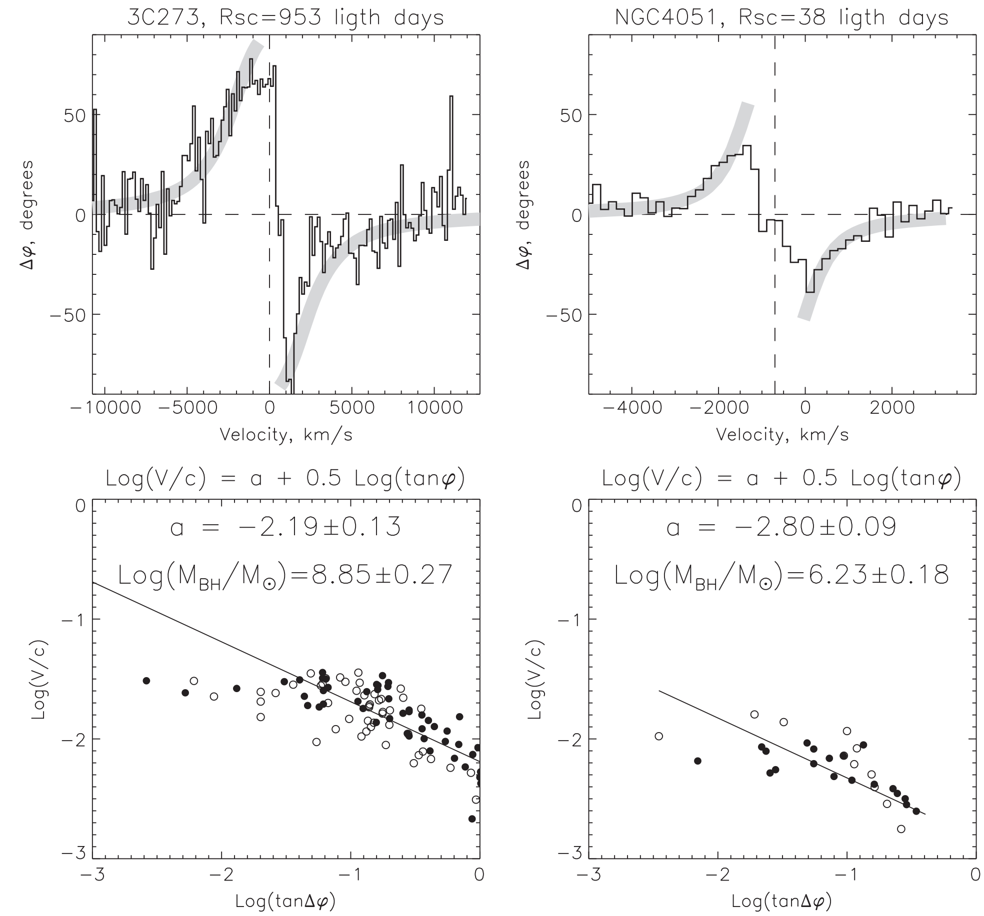

Figure 2. Observed shape of ($\Delta\varphi$) (upper panels) and velocities (lower panels) across the H line profile and 3C273 (left panels) and NGC 4051 (right panels) for the AGNs in our sample with the highest and lowest masses, respectively. The filled circles are from the blue line part, and the open circles are from the red line part. The gray curves in the upper panels are expected $\Delta\varphi$ for estimated black hole masses.

Bentz et al. 2007; Denney et al. 2010; Grier et al. 2012), and we compare these with our spectropolarimetric estimates (see Figure 3). As can be seen in Figure 3, there is a good agreement between our measurements and the reverberation ones. This supports the validity of our proposed method, and the good correlation between line polarization and reverberation mapping masses strongly supports our assumption that the scattering region is at or near the inner radius of the torus.

Our method offers a number of advantages over traditional reverberation mapping (see Peterson 2014). The first and most fundamental advantage is that our estimates of SMBH masses do not depend on the BLR inclination and geometry, i.e., the additional effects to the rotation of the BLR as outflows/inflows, which may strongly affect the broad-line profiles (especially widths, which have been used in the reverberation method), do not change the PA shape across the line profile that is used in this method. These effects can be seen only as a velocity shift of the PA center (see Figure 2). A second advantage is that our method only needs one epoch of observation while reverberation mapping is very telescope-time intensive. A third advantage is that while in the reverberation method it has to be assumed a priori that the BLR is virialized, in using the spectropolarimetric method, one can test the assumed Keplerian motion (i.e., virialization) using the relationship between $\Delta\varphi$ and velocities across the broad-line profile (see Equation (2) and Figure 2). Finally, another significant advantage of our method is that, in principle, it can

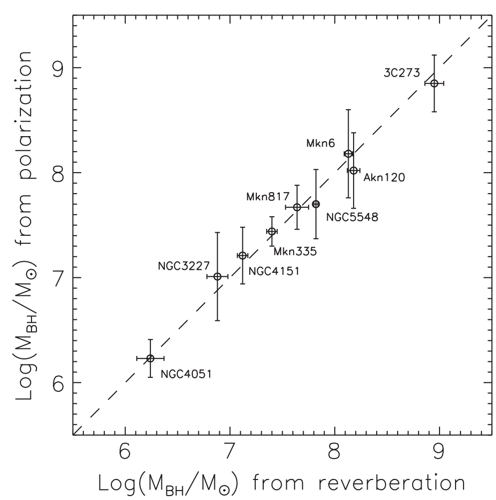

Figure 3. Comparison between black hole masses obtained by our spectropolarimetric method with reverberation estimates in the literature (see Table 1).

be applied to lines from different spectral ranges going all the way from the near-infrared and optical (such as the Balmer lines used as in this paper) to the UV (e.g., Lyα, C III], C IV, and Mg II) so long as the variation in PA of the polarization can be measured. This thus allows measurement of black hole masses in a consistent way at different cosmological epochs. Doing this in practice requires the development of high-quality spectopolarimetric instrumentation.

On the other hand, there are some problems with the application of the method to some AGNs: (1) the inner torus radius measurement is needed for the black hole mass estimates, which can be found by using the reverberation method in the infrared (2–3 μm; see Kishimoto et al. 2011) for low-redshift AGNs and using the calibration between the inner torus radius and the UV radiation for high-redshift quasars (see e.g., Barvainis 1987); (2) the method can be used only for a rotating BLR disk, and in the case of the BLR with a dominant radial component (without significant rotation), the method cannot be used. It may be a problem with high ionized lines, such as C IV and C III]; however, the high ionized line profiles indicate a Keplerian motion component (see, e.g., Clavel et al. 1987). In the near future, we are going to perform new spectopolarimetric observations of high-redshift quasars in the UV lines.

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