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Black hole mass measurements in AGN: Polarization in broad emission lines

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Abstract. We present a new method for supermassive black hole (SMBH) mass measurements in Type 1 active galactic nuclei (AGN) using polarization angle across broad lines. This method gives measured masses which are in a good agreement with reverberation estimates. Additionally, we explore the possibilities and limits of this method using the STOKES radiative transfer code taking a dominant Keplerian motion in the broad line region (BLR). We found that this method can be used for the direct SMBH mass estimation in the cases when in addition to the Kepler motion, radial inflows or vertical outflows are present in the BLR. Some advantages of the method are discussed.

Keywords. polarization, spectral line shapes, active galactic nuclei, black holes: masses

1. Introduction

Supermassive Black Holes (SMBHs, $10^6 - 10^9\ M_\odot$) are supposed to reside in the bulges of spiral and elliptical galaxies, and they are in action to shape their cosmic environment, i.e. it seems that there is a connection between the central SMBH and the host galaxy structure. The close connection between the formation and evolution of galaxies and of their central SMBHs involves a variety of physical phenomena of great relevance in modern astrophysics (see e.g. Heckman & Best 2014). The parameters which define a SMBH are mass, spin and electricity, where mass of SMBH is the most important and probably is in the correlation with the galaxy bulge mass. Therefore, one of the most important issue in astrophysics today is to measure masses of SMBHs.

One of the most powerful objects in the Universe are active galactic nuclei (AGNs) which emit huge amount of energy that is created around SMBHs. The emission gas is very close to the central SMBH, and therefore the gas kinematics is directly influenced by the mass of the central black hole. Especially if the gas emits the broad lines from the so called broad line region (BLR). The width of lines emitted from the BLR corresponds to the rotational velocity that can be used for estimation of the black hole masses in AGNs.

In principle there are several methods for the SMBH mass measurements (see Peterson 2014), out of which the reverberation method is the one often used in the case of AGNs. Using this method one can estimate the SMBH mass as:

$$M_{\rm BH} = f\,\frac{R_{\rm BLR}\sigma_V^2}{G},$$

where $R_{\rm BLR}$ is the photometric dimension of the BLR obtained from the reverberation mapping, and σ_V is the corresponding orbital velocity that can be estimated from the broad line widths. G is the gravitational constant and the virial factor f depends on the BLR inclination and geometry which are unknown and, consequently there is a problem to accurately determine the virial factor (Peterson 2014).

On the other side, the polarization in the broad lines can be very useful for investigation of the nature of the BLR (Smith *et al.* 2002, 2004, 2005; Afanasiev *et al.* 2014; Afanasiev & Popović 2015, Afanasiev *et al.* 2018 etc.). The polarization in the broad lines, especially the polarization angle (φ) that shows horizontal S shape across the broad line profile, which indicates a dominant Keplerian-like motion in the BLR, and dominant equatorial scattering as a polarization mechanism in the broad lines (see Afanasiev & Popović 2015).

In this contribution we shortly describe the method and give some overview of the numerical tests of the validity (limitations) of the method which have been performed by STOKES code (see Savić *et al.* 2018)

2. Polarization method for SMBH measurements

The method is described in more details in Afanasiev & Popović (2015). We used the fact that in the case of equatorial scattering, the polarization angle (φ_i) is connected with the distance (R_i) of an emitting cloud (see Fig. 1 in Afanasiev & Popović 2015) as

$$\tan \varphi_i \sim R_i,$$

that in the case of a Keplerian like motion can be connected with the velocity ($V_i = (\lambda_i - \lambda_0)/\lambda_0$, where λ_0 is the transition wavelength) of the emitting cloud (i.e. λ_i is the wavelength emitted by the cloud) as

$$V_i = \sqrt{\frac{GM_{\rm BH}}{R_i}},$$

where $M_{\rm BH}$ is the mass of SMBH.

It is not difficult to obtain that $R_i = R_{sc} \cdot \tan \varphi_i$, where $R_{\rm sc}$ is the the distance between the SMBH and the scattering region (supposed to be in the inner part of the torus, see Fig. 1 in Afanasiev & Popović 2015). Considering the above relations one can obtain the relationship between the velocity (V_i) and $\tan \varphi$ as:

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

where c is the speed of light, and constant a depends on the SMBH mass ($M_{\rm BH}$) as

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

that can be used for the SMBH mass measurements.

We show in Afanasiev & Popović (2015) that the method gives SMBH mass estimates which can be compared with the reverberation mapping results. The method seems to be very perspective, since, as it can be seen in Fig. 1 (left panel), very often we can observe a horizontal S-shaped polarization angle in the case of Type 1 AGNs (AGNs with the broad emission lines, see Afanasiev *et al.* 2018).

3. Modeling and method validity and limitations

Following the method described by Afanasiev & Popović (2015), we theoretically model the broad line polarization due to equatorial scattering. We assume that the unpolarized lines are emitted from the disk-like BLR with dominant Keplerian motion and scattered by free electrons at the inner part of the dusty torus. We used 3D Monte Carlo radiative

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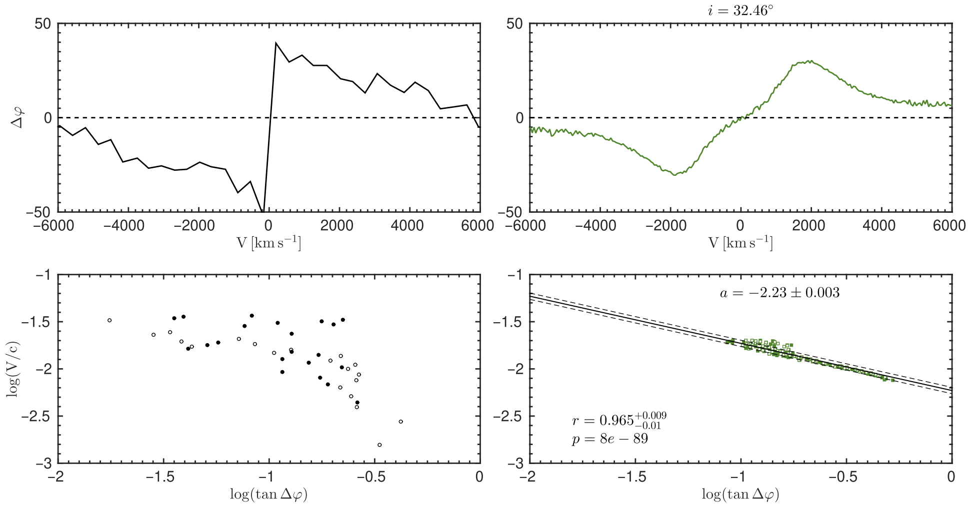

Figure 1. The observed (left) and modeled (right) polarization angle changes across the Hα line profile (panels up) for NGC 4151 and $\log(\frac{V}{c})$ vs. $\tan(\Delta\varphi)$ (panels down) relationship (in more detail see Savić *et al.* 2018).

transfer code STOKES (see, e.g. Goosmann & Gaskell 2007, Marin *et al.* 2015, Marin 2018, Rojas Lobos *et al.* 2018). The size of the BLR was obtained from the reverberation mapping with the outer edge set due to dust sublimation. Model parameters of the BLR and the scattering region (SR) are described in more details in Savić *et al.* (2018), and here will not be repeated. The models are showing that the mass estimates with the polarization method are in the frame of 10% error-bars in the case that the SR distance which is twice the size of the outer limit of the BLR. The largest number of photons is scattered only once from the inner edge of the SR. The number of multiple scattering events is negligible and the assumption of a single scattering approximation is valid. In Fig. 1 (right panel) we show the modeled polarization angle across the broad Hα profile for NGC 4151, and as one can see from Fig 1, the modeled profile is very similar to the observed one. Also the relationship between velocity and $\tan\varphi$ across the line profile can be reproduced (Fig 1. bottom panels). This indicates that the single element equatorial approximation is valid.

Additionally, we considered the possible inflows/outflows in the BLR (see Savić *et al.* 2018) and we have shown that the method for SMBH mass measurements can be used when the contribution of the inflows/outflow is much smaller in comparison with Keplerian motion. Therefore, this method could potentially be used for highly ionized lines such as C III] and C IV that are observed in the optical domain for high-redshifted quasars.

For high inclinations, the polar scattering becomes dominant and we have Type-2 objects for which the method is no longer valid. For face-on AGNs, the optical polarization is usually much lower than 1% (Smith *et al.* 2002, Marin 2014) and the amount of interstellar polarization can dominate the equatorial scattering induced polarization in the innermost part of the AGNs. The variability of Type-1 AGNs must also be taken into account. The flux variations of the continuum and broad lines can be up to a factor of 10 or greater between minimum and maximum activity state (Shapovalova *et al.* 2008, 2010). When observed in the minimum activity (up to Type-2), the absence or the weak flux in the BLRs could not be detected and the method cannot be used.

4. Discussion and conclusions

In this paper we shortly describe the polarization method for the SMBH mass measurement using the shape of polarization angle across the broad line profiles (Afanasiev *et al.* 2014, Afanasiev & Popović 2015, Savić *et al.* 2018). We found that our method gives very good results in comparison with the reverberation one.

As conclusions we can list the advantages and disadvantages of the method. First, let us mention the advantages, which are: i) the method does not need assumption of virialization (as in the case of the reverberation one), since the horizontal S-like shape of polarization angle across the broad line indicates presence of the Keplerian-like motion (see Fig. 1); ii) the method is not time consuming, i.e. from one epoch observation of broad line, one can obtain the SMBH mass; iii) the method can be applied to all broad lines from the UV to the optical, i.e. one can measure the SMBH mass of different redshifted AGNs in the same (consistent) way.

On the other hand, there are some disadvantages of the method which are: i) the polarization in the broad line of AGNs is not so big, therefore the effect can be hidden by the other (additional) effects of polarization or depolarization; ii) in the case of very strong outflow and inflows, the effect cannot be clearly seen, and could not be used for the SMBH mass determination and iii) there can be a problem with the estimation of distance of the equatorial scattering region (R_{sc}).

Finally, let us conclude that the method is very useful and it represents a new method for the SMBH mass determination that can be used also in the case of high redshifted AGNs.

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