Weighing black holes in radio-loud AGNs

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Abstract. Because of the contamination of jets, using the size – continuum luminosity relation can overestimate the broad line region (BLR) size and black hole mass for radio-loud AGNs. We propose a new relation between the BLR size and Hβ emission line luminosity and present evidences for using it to get more accurate black hole masses of radio-loud AGNs. For extreme radio-loud AGNs such as blazars with weak/absent emission lines, we suggest to use the fundamental plane relation of their elliptical host galaxies to estimate the central velocity dispersions and black hole masses, if their host galaxies can be mapped.

1. Introduction

Dynamical measurements clearly indicate that supermassive black holes exist in the center of nearby galaxies. However, dynamical methods can not be applied to most of AGNs because they are too bright. Currently the most reliable method for AGN black hole mass estimation is the reverberation mapping. Using this technique, the BLR size can be measured using the time lag between the variations of continuum and emission line fluxes. The black hole mass can be derived from the BLR size and the characteristic velocity using the virial law. So far, reverberation mapping studies have yielded black hole masses of about 40 Seyfert 1 galaxies and nearby quasars (Kaspi et al. 2000, 2005; Peterson et al. 2004). Using the observed data of these reverberation mapping AGNs, an empirical relation between the BLR size (R) and continuum luminosity at 5100Å (L_{5100}) has been derived by Kaspi et al. (2000, 2005), which has been frequently adopted to estimate the BLR size and the black hole masses for large samples of AGNs, including radio-loud quasars. However, the optical continuum luminosity of radio-loud AGNs may not be a good indicator of ionizing luminosity. Powerful jets of blazar-type AGNs may significantly contribute to the optical continuum luminosity. Therefore, using the R – L_{5100} relation may significantly overestimate the actual BLR size and the black hole mass of radio-loud AGNs. In addition, another tight correlation between black hole mass and bulge velocity dispersion (σ) has been found for nearby galaxies (Tremaine et al. 2002) and for a few Seyfert galaxies as well (Ferrarese et al. 2001). Such a relation suggests a possibility to estimate the black hole masses of AGNs using the measured bulge velocity dispersions. Especially for BL Lacertae objects, the
reverberation mapping technique cannot be applied because they show no or weak emission lines in their optical spectra. Using the $M_{BH}-\sigma$ relation may be the only way to derive their black hole masses, though measuring $\sigma$ is possible only for nearby sources.

In this presentation we report our recent progress on estimating the black hole masses of radio-loud AGNs using a new BLR size – $H_\beta$ emission line luminosity relation and the fundamental plane relation of the elliptical host galaxies.

2. The BLR size – $H_\beta$ luminosity relation

Using the available data of BLR sizes and $H_\beta$ fluxes for 34 AGNs in the reverberation mapping studies, we investigated the relation between the BLR size and the $H_\beta$ emission line luminosity (Wu et al. 2004). An empirical relation between the BLR size and $H_\beta$ luminosity was derived as:

$$\log R (\text{lt - days}) = (1.381 \pm 0.080) + (0.684 \pm 0.106) \log (L_{H_\beta}/10^{42} \text{ ergs s}^{-1}).$$ (1)

The Spearman’s rank correlation coefficient of this relation is 0.91. In the left panel of Fig. 1 we show the dependence of the BLR size on $L_{H_\beta}$ and $L_{5100 \text{A}}$. Obviously these two relations are similar, which means that the $R - L_{H_\beta}$ relation can be an alternative of the $R - L_{5100 \text{A}}$ relation in estimating the BLR size for radio-quiet AGNs. We applied both the $R - L_{H_\beta}$ and $R - L_{5100 \text{A}}$ relations to estimate the black hole masses of 87 radio-loud quasars and compare them in the right panel of Fig. 1. Evidently the masses obtained with the $R - L_{H_\beta}$ relation are systematically lower than those obtained with the $R - L_{5100 \text{A}}$ relation for some extremely radio-loud quasars. The difference between two black hole mass estimates is particularly large for sources with radio luminosities greater than $10^{24}$ ergs s$^{-1}$. These results provide additional evidence for the fundamental plane relation of the elliptical host galaxies.
mass estimates is smaller when the radio-loudness is small but becomes larger as the radio-loudness increases. For some individual quasars with higher radio-loudness, the black hole mass estimated with the $R - L_{5100\text{Å}}$ relation can be 3~10 times larger than that estimated with the $R - L_{H\beta}$ relation. Recently Kong et al. (2006) also extended such a study to the broad UV emission lines MgII and CIV, and obtained the BLR size – UV emission line luminosity relations. Liu, Zhao, & Wu (2006) applied the $R - L_{H\beta}$ relation to a well studied BL Lac object AO 0235+164 and estimated its black hole mass as $5.8 \times 10^8 M_\odot$, which is consistent with the mass ($3.6 \times 10^8 M_\odot$) estimated from the $M_{BH} - \sigma$ relation by taking the narrow emission line width as a surrogate of $\sigma$, but is much smaller than the mass ($1.5 \times 10^9 M_\odot$) obtained from the $R - L_{5100\text{Å}}$ relation. This again demonstrates that using the $R - L_{5100\text{Å}}$ relation can overestimate the black hole masses of blazar-like AGNs.

3. Black hole masses estimated from the fundamental plane relation of AGN elliptical host galaxies

For radio-loud AGNs such as BL Lacs with weak/absent emission lines, the emission line based methods for black hole mass estimations can not apply. Directly measuring their stellar velocity dispersion is also difficult. However, the host galaxies of BL Lacs are virtually ellipticals. It is well known for ellipticals that three observables, namely the effective radius ($R_e$), the average surface brightness ($<\mu_e>_R$ in R-band) and the central velocity dispersion ($\sigma$), follow a tight fundamental plane relation. For about 300 normal ellipticals and radio galaxies, Bettoni et al. (2001) found that the fundamental plane can be robustly described as

$$\log R_e = (1.27 \pm 0.04) \log \sigma + (0.326 \pm 0.007) <\mu_e>_R - 8.56 \pm 0.06,$$

(2)
This relation provides us another way to estimate the central velocity dispersions and then the black hole masses of AGNs (Wu, Liu & Zhang 2002).

Using the imaging data of BL Lacs obtained from the HST snapshot survey (Urry et al. 2000), we adopted the fundamental plane relation to estimate the central velocity dispersions and black hole masses of 51 high-frequency peaked BL Lacs (HBLs) and 12 low-frequency peaked BL Lacs (LBLs). Our results show no significant difference in the black hole masses between HBLs and LBLs (see the left panel of Fig. 2). We also applied the same method to 10 radio galaxies (RGs), 10 radio-loud quasars (RLQs) and 13 radio-quiet quasars (RQQs) which have been imaged by HST (McLure et al. 1999), we found that there are no significant differences in the black hole masses among these different types of AGNs with elliptical host galaxies (see the right panel of Fig. 2). As another example, we also applied this method to a well-known BL Lac object OJ 287 (Liu & Wu 2002). We estimated its primary black hole mass to be about $4 \times 10^8 M_\odot$, which is consistent with the upper limit ($10^9 M_\odot$) obtained by Valtaoja et al. (2000) based on a new binary black hole model for OJ 287.

4. Summary

We proposed to use the BLR size – emission line luminosity relation and the fundamental plane relation of the elliptical host galaxies to estimate the black hole masses of radio-loud AGNs. We demonstrated that with the first relation we can get more accurate black hole mass estimates for radio-loud AGNs than using the usual $R - L_{5100}$ relation, and for some radio-loud AGNs such as BL Lacs the second method is probably the only available one for their black hole mass estimations in the case when directly measuring the stellar velocity dispersions is difficult. Finally we would like to mention that these two methods can be also applied to estimate the black hole masses of high redshift AGNs with high quality spectroscopic and imaging observations.

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