Models of Continuum of Weak Emission-Line Quasars

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We study optical-ultraviolet spectral energy distribution (SED) of 10 weak emission-line quasars (WLQs) at redshifts z = 0.19 and 1.43 < z < 3.48. The theoretical models of their accretion disc continua are created based on the Novikov-Thorne equations. It allows us to estimate masses of their supermassive black holes, and accretion rates. We determine the virial factor for WLQs and note its anti-correlation with the full width at half maximum ($FWHM$) of Hβ emission-line ($f \propto FWHM^{\alpha}, \alpha = -1.34 \pm 0.37$). In our opinion, WLQs are normal quasars visible in a reactivation stage.

1 Introduction

Weak emission-line quasars (WLQs) are interesting and enigmatic objects. Their nature is still unknown. There are a few explanations of the intrinsically weakness of WLQ: 1) a radiatively inefficient accretion flow (Yuan & Narayan, 2004) or an cold accretion disc (Laor & Davis, 2011), 2) high accretion rate with inefficient photoionized flux (Leighly et al., 2007a,b), 3) presence of shielding gas between the accretion disc and a Broad Line Region (BLR) (Wu et al., 2011), 4) the early stage of AGNs evolution (e.g. Hryniewicz et al., 2010; Bañados et al., 2014). The goal of this paper is investigate the mass of black hole and determine the virial factor for WLQ.

2 Method

We fitted SED of quasars by the simple geometrically thin and optically thick accretion disc (AD) model described by Novikov & Thorne (NT) equations. The output continuum of the NT model is fully specified by four parameters, which we determine: the black hole mass – $M_{\rm BH}$, the mass accretion rate – $\dot{M}$, the dimensionless spin[1] – a_*, and the inclination – i at which an observer looks at the AD. The mass of the black hole is expressed in units of mass of the Sun ($M_\odot$), and the accretion rate in the form of the Eddington rate, i.e. $\dot{m} = \dot{M}/\dot{M}_{\rm Edd} \propto \dot{M}/M_{\rm BH}$. We constructed a grid of 366000 spectral models of AD, for evenly spaced values of $M_{\rm BH}$, $\dot{m}$, a_*, and i. The $\log M_{\rm BH}$ range is from 6.0 to 12.0, the Eddington accretion rate covers the band 0–1, and the dimensionless spin $0 \leq a_* \leq 0.9$ with the step 0.1. The inclination is fixed for 6 values that cover a range from 0° to 75° with the step of 15°. We compute spectra as multicolor black body emission with code based on NT equations. The spin is affected the spectra in whole range. We used correction factor $f_{\rm R}(a_*) \equiv \frac{Q}{BC^{1/2}}$ where Q,B and C are dependent on the spin value (Kato et al., 1998) and appendix herein.

[1] $a_* = \frac{cJ}{GM^2}$

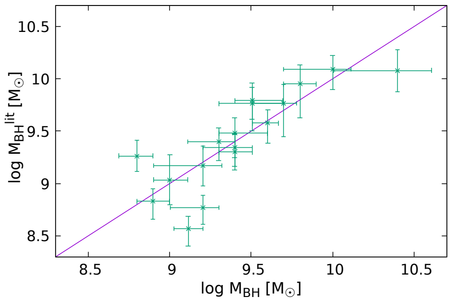

Fig. 1: Comparison of LBQS masses based on Vestergaard & Osmer (2009) (on Y-axis) with $M_{\rm BH}$ from our model (on X-axis). Violet solid line is identity 1:1 line.

To find the best-fit model and to evaluate the quality of the fit, we used a simple χ^2 procedure, which is based on directly matching the photometric points to the AD model. In our approach, we calculate $\chi^2 = \sum_{i=1}^{n}(O_i - E_i)^2/\sigma_i$ for each quasar, where O_i and E_i are observed and modeled monochromatic luminosities L_λ, respectively, read out at wavelength corresponding to the ith photometric point. σ_i is the observed error, and n – total number of observed data for the quasar. Satisfactory fits are defined as those showing reduced $\chi^2 < 5.5$.

Our sample contains 10 WLQs. Their photometric points at visible wavelengths are collected based on the Sloan Digital Sky Survey (SDSS) optical catalogue Data Release 7, which contains u, g, r, i, and z photometry (Abazajian et al., 2009). Near-infrared photometry in the W1-W4 bands are taken from the Wide-field Infrared Survey Explorer (WISE) Preliminary Data Release (Wright et al., 2010; Wu et al., 2012). The photometry in the J, H, $\rm K_S$ colours were obtained from the Extended Source Catalog of the Two Micron All Sky Survey (2MASS) (Skrutskie et al., 2006). Those ones detected in near- and far-ultraviolet (NUV, FUV, respectively) wavelengths were taken from the Galex Catalogue Data Release 6 (Bianchi et al., 2017; Seibert et al., 2012).

To check the disc fitting method with respect to WLQs, we analysed a method on a sample of normal type 1 quasars. We selected the sample of objects taken from the Large Bright Quasar Survey (LBQS) (Hewett et al., 1995, 2001). We have chosen 27 quasars with redshift between 0.254 and 3.36 and the presence of a well visible big blue bump. We have taken the logarithm of masses of supermassive black holes, $\log M_{\rm BH}$ ($\rm M_\odot$), from 8.09 to 10.18, and luminoisities, $\log L_{\rm bol}$ (erg s^{-1}), in the range 45.25 to 47.89. The photometric points of selected quasars came from the same catalogues mentioned earlier. The obtained SED of all objects are corrected for Galactic reddening (Cardelli et al., 1989; Fitzpatrick, 1999).

3 Results

For initial analysis, we used 27 quasars from the LBQS survey. Fig.1 shows a comparison of the supermassive black hole masses determined by Vestergaard & Osmer (2009) used the black hole mass determination based on their formula (Eq. 1. in their paper), which is proportional to $FWHM$(line) and continuum luminosity νL_ν, which is close to the line but without a contamination of lines. Compliance of

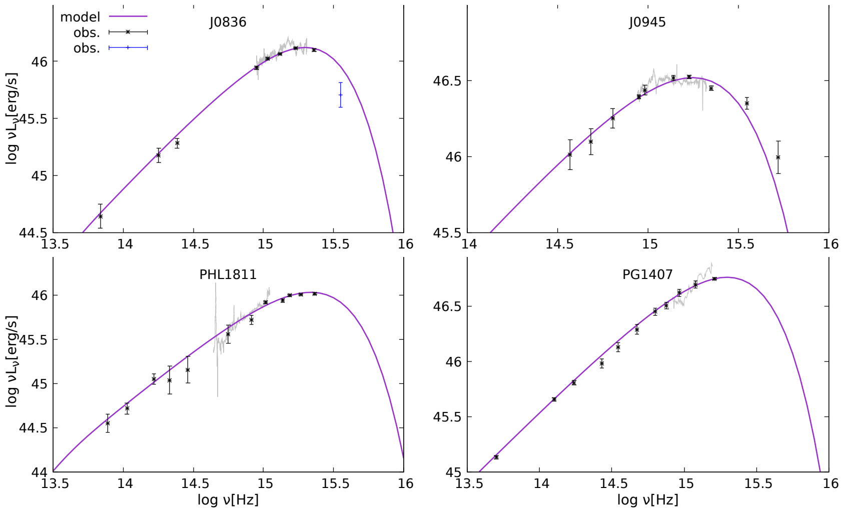

Fig. 2: Some of the best fit of SED to photometric points of WLQs. Black crosses and blue with errors show corrected observational data, grey line – spectra. Violet solid line represents the theoretical curve of continuum model.

masses and relatively small distribution of errors means that the continuum fitting method applies to quasars. Performed analysis enable us to estimate the accretion efficiency, η. In order to bring the masses into conformity, it is necessary to adopt $\eta = 0.15 - 0.20$. We take the same value of $\eta = 0.18$ in relation to WLQ and LBQS.

Our sample of WLQs contains 10 objects. In Fig.2 we present the best fits of disc continua that match the quasar SED. The presented mass comparison suggests that literature determinations of black hole masses, $M_{\rm BH}^{\rm lit}$, based on $FWHM(\mathrm{H}\beta)$ are generally underestimated, as presented in Fig. 3 left panel. We also determined the difference between $M_{\rm BH}^{\rm lit}$ and $M_{\rm BH}$ values. The γ factor is calculated ($\gamma = M_{\rm BH}/M_{\rm BH}^{\rm lit}$). In Fig. 3 right panel, we present the relationship between the logarithmic value of $FWHM(\mathrm{H}\beta)$ in km s^{-1} and the logarithmic value of the γ factor. The green solid line shows the best fit between those variables. The fit is made using the nonlinear least-squares (NLLS) Marquardt-Levenberg algorithm which takes into account errors in both x and y directions. The derived relationship is:

$$\log\gamma = (-1.338 \pm 0.366) \times \log\left(\frac{FWHM(H_\beta)}{10^3\,\mathrm{km\,s}^{-1}}\right) + (1.294 \pm 0.234)\,. \qquad (1)$$

The virial factor is often assumed to be constant with values of 0.6–1.8 (e.g. Peterson, 2004; Nikołajuk et al., 2006), where 0.75 corresponds to a spherical geometry of the BLR. Generally, f dependents on non-virial velocity components (e.g. winds), the relative thickness ($H/R_{\rm BLR}$) of the Keplerian BLR orbital plane, the line-of-sight inclination angle (i) of this plane, and the radiation pressure (e.g. Gaskell, 2009; Denney et al., 2010; Shen & Ho, 2014) and it should be a function of those phenomenons. The analysis carried out by Mejía-Restrepo et al. (2018) indicates a low influence of radiation pressure on the f factor, however this mechanism cannot be excluded. Whether or not we skip the radiation pressure influence, the line-of

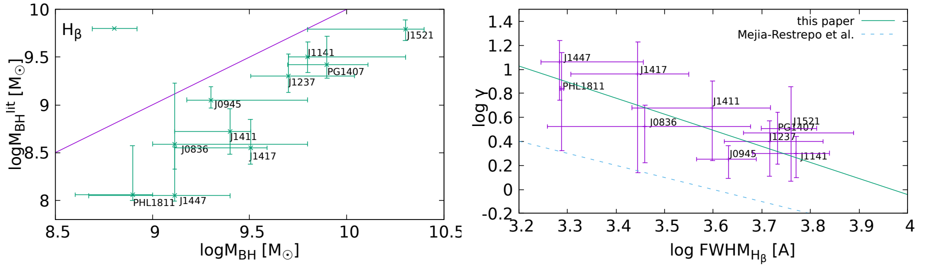

Fig. 3: Left panel: the comparison of SMBH masses ($M_{\rm BH}^{\rm lit}$) of WLQs with $M_{\rm BH}$, that come from spectral fitting method. Violet solid line is identity 1:1 line. Green crosses represent $M_{\rm BH}^{\rm lit}$ calculated using $FWHM(\mathrm{H}\beta)$. Right panel: the γ factor ($= M_{\rm BH}/M_{\rm BH}^{\rm lit}$) versus $FWHM(\mathrm{H}\beta)$. The best fit (i.e. $\gamma \propto FWHM^{-1.34}$) is shown by green solid line. Points show data of 10 WLQs. The blue dash line represents the fit of the virial factor (i.e. $f \propto FWHM^{-1.17}$) to 37 AGNs made by Mejía-Restrepo et al. (2018). In our case $\gamma = \mathrm{const} \times f$ and the dash line is shifted down.

sight inclination of gas in a planar distribution of the BLR plays important role in black hole mass calculations. Unfortunately, the nature of the velocity component responsible for the thickness of the BLR and thus its geometry is unclear (e.g. Done & Krolik 1996; Czerny et al. 2016; for recent review see Czerny 2019). There is accumulated evidence in the literature favouring a disc-like geometry for the BLR and/or clouds (e.g. Laor et al., 2006; Pancoast et al., 2014).

Our results support those obtained by Mejía-Restrepo et al. (2018). They studied 37 AGNs at redshifts ~ 1.5. The authors indicated the dependency of the virial factor, on observed $FWHM$ of the broad emission-line (such as $H\beta$, MgII, CIV) in the form of the anti-correlation. Mejía-Restrepo et al. (2018) find that the dependence of $M_{\rm BH}$ on the observed $FWHM$ of the Balmer lines for AGNs is close to linear rather ($M_{\rm BH}\propto$ $FWHM(\mathrm{H}\beta)^{0.82\pm0.11}$), than quadratic ($M_{\rm BH}\propto$ $FWHM^2$ function of $FWHM$). In our case this relationship for WLQs is bit weaker ($M_{\rm BH}\propto$ $FWHM(\mathrm{H}\beta)^{0.66\pm0.37}$), but still compatible with the Mejía-Restrepo et al. result within 1σ error. A similar or even the same behaviour of normal AGNs and WLQs suggests that both kind of sources have the same dim nature of the velocity component and the same geometry of the BLR. Systematic underestimation of $FWHM$ (and $M_{\rm BH}^{\rm lit}$) may be caused by a strong influence of the FeII pseudo-continuum in optics. Such phenomena is noticed by Plotkin et al. (2015) for their sample of WLQ, which have larger $R_{\rm opt,FeII}$ and narrower Hβ than most reverberation mapped quasars.

4 Conclusions

Our main findings are: 1) Using the Novikov-Thorne model, we can describe very well the SED of WLQs. 2) The SMBH masses of WLQs, which are estimated based on $FWHM(\mathrm{H}\beta)$, are underestimated. On average, the masses are undervalued 4-5 times. The median of this correction factor is 3.3. 3) We support Mejía-Restrepo et al. result and confirm that the virial factor, f, depends on $FWHM$ ($\propto FWHM(\mathrm{H}\beta)^{-1.34\pm0.37}$). The BLR is non-spherical region. 4) We suggest that WLQs are normal quasars in an reactivation stage.

Acknowledgements. We thank to Bozena Czerny for helpful feedback and discussions. The authors acknowledge support from the Polish National Science Center Grant No. 2016/22/M/ST9/00583.

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