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SEARCHING FOR EXTREMELY ACCRETING QUASARS

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Abstract. Quasars are most luminous objects and therefore can be detected as far as the edge of the known Universe. As such they could be useful for measuring cosmological distances. The problem is that quasars show large diversity in their properties – their luminosity is spread over six orders of magnitudes, that makes them not suitable for conventional standard candles. A sub-group of quasars, called highly or extremely accreting quasars (xA quasars) radiate close, or even above Eddington luminosity. They are extreme in many aspects – xA quasars are among quasars with highest accretion rates, and their emitting line regions show the lowest ionization parameter and the highest electron density. We focus on low-z xAs with high host galaxy contribution and also strong FeII emission lines in their optical spectra. They share several other multi-frequency properties which can be used for their identification. Our ability to distinguish xA quasars as sources whose Eddington ratio is extreme and ideally scattering little around a well-defined value opens up the possibility to use these quasars as potential cosmological probes. We address problems that could lead to misidentification of xA quasars using optical spectra.

1. INTRODUCTION

Back in 1929 Edwin Hubble discovered the expansion of the Universe using velocity - distance relation among nearby extra-galactic nebulae - the distance modulus is increasing with the redshift. It was a discovery that scientists until nowadays try to apply to higher distances. In order to measure distance in the Universe it is crucial to choose a sample of standard candles - objects with known luminosity. For a very long period of time, type Ia supernovae and variable stars such as Cepheids have been used as standard candles with very high precision (see e.g. Kirchner 2004, Rubin et al. 2012). The problem is that supernovae can be detected only up to $z \sim 1.3$.

Quasars are objects that can be observed at all redshift scales - from our "vicinity" till the edge of the known Universe (up to $z \sim 7.6$). Besides, they are the most luminous sources in the Universe, whose bolometric luminosity can reach up to $10^{48}\mathrm{erg\,s^{-1}}$. Quasars are easily recognizable and numerous. Up to now, more than 750,000 quasars have been discovered (see SDSS DR 16, Lyke et al. 2020). For these reasons, there were many attempts to use quasars as standard candles or as standard rulers. But, the main problem is that - even though quasars are the most luminous objects in the Universe, and therefore easily detectable, their luminosity is spread over six orders of magnitude, making them opposite of what standard candles by definition are. Besides, they are highly variable sources in luminosity and spectral energy distribution and their spectral properties do not show strong signs of a luminosity dependence. Moreover, quasars are anisotropic sources. So, the goal should be to find one or more parameters closely related to the intrinsic luminosity of quasars, or in other words, to isolate class of quasars with a constant characteristic, that we can use for redshift-independent estimate of luminosity.

There were several tentative experiments to use quasars in the context of distance measurements:

- ”Baldwin effect“ - Baldwin (1977) noticed that the equivalent width of emission line (such as CIV λ1549) decreases as the UV continuum luminosity (λ 1450) increases. It was believed that the redshift independency of flux ratio used to obtain equivalent width could be used for distance measurements, but a large dispersion in this anticorrelation (e.g., Baldwin, Wampler, & Gaskell 1989) returns distance calibrations of a low quality in comparison with other standard candles.

- BLR reverberation - The reverberation studies showed a tight relation between the delay (τ) of the emission line and the intrinsic luminosity (most frequently calculated from the flux measured at 5100 Å (F_{5100}) (e.g., Peterson et al. 1999, Kaspi et al. 2000)). Line delay can be explained as an effective radius of the BLR region, related with the luminosity as $r_{BLR} \sim L^{1/2}$ (Watson et al, 2011). The dispersion in the $r_{BLR} - L$ relation is low. Bentz et al. (2013) measured the dispersion of only 0.13 dex in clean sample. Therefore, with a larger sample and broader coverage of the redshift range this method could present a very good alternative to type Ia supernovae.

- Continuum reverberation - The observed delays between different continuum wavelengths depend on the disk’s radial temperature distribution, its accretion rate, and the central black hole mass. Wavelength - dependent continuum time delays can be used to calculate the AGN distance (Collier et al. 1999), knowing the accretion disk flux, which can be obtained by taking difference spectra to isolate the variable component of AGN light.

- Dust reverberation - The dust reverberation allow us to derive the inner radius of the dust torus by measuring the lag between the flux variation of the UV/optical continuum from the accretion disk and that of the near-infrared thermal emission from the dust torus. The inner radius of the dust torus is expected to be proportional to the square-root of the accretion-disk luminosity, and that opens the possible application of the dust reverberation to the cosmological distance measurement (Kobayashi et al. 1998).

Even though reverberation methods offer promising possibilities to use quasars as standard candles, objects monitored in reverberation campaigns are most often on low z scales. Besides, monitoring is usually very time consuming.

Therefore these methods have not been until now efficient to build samples with large number of sources that could be used in cosmological studies. The following methods use single observations for cosmological studies, and hence are more appropriate for making large samples of objects of interest:

- X-ray excess variance method - La Franca et al. (2004) proposed the method to determine the absolute luminosity from the X-ray excess variance and the full width half maximum (FWHM) of Hβ emission line. The method requires a single optical spectrum of an object, but the difficulty lies in the high quality measurement of the high frequency tail of the X-ray power spectrum. Hopefully, the Athena X-ray Observatory, expected to be launched in 2028, will provide significant number of measurements.
- Super Eddington black holes - In a super-Eddington accretion regime a “thick disk” is expected to develop (Abramowicz et al. 1988). The accretion flow remains optically thick so that radiation pressure “fattens” it. When the mass accretion rate becomes super-Eddington, the emitted radiation is advected toward the black hole, so the radiative efficiency of the accretion process is expected to decrease, causing an asymptotic behavior of the luminosity as a function of the mass accretion rate (Wang et al. 2014).
- Continuum shape method - This method proposed to use the non-linear relation between X-ray and UV emission as an absolute distance indicator (Lusso & Rissality, 2015). This relation implies that quasars more luminous in the optical are relatively less luminous in the X-rays. This is the first successful method for measuring distances on a high redshifts (up to z $\sim$ 6), using quasars as standard candles.

If Eddington ratio and black hole mass can be derived from some distance-independent measure it would be possible to derive distance-independent quasar luminosities. Marziani & Sulentic (2014) succeeded to isolate a subclass of quasars -xA quasars or extreme accretors - that radiate close to the Eddington limit, and show distinct optical and UV spectral properties that can be recognized in spectra. They propose precise criteria based on the line ratios (AlIIIλ1860/SiIII]λ1892 $\geq$ 0.5, and (ii) SiIII]λ1892/CIIIλ1909 $\geq$ 1.0) which lead to a source sample with very low dispersion of $\sim$ 0.13 dex in the Eddington ratio. The major issue related to the cosmological application of the xA quasar luminosity estimates from line widths is the identification of proper emission lines whose broadening is predominantly virial over a wide range of redshift and luminosity. At lower redshift the good virial estimator is Hβ emission line, while on higher redshifts, AlIIIλ1860 can be used with the same purpose (Marziani & Sulentic 2014, Negrete et al. 2018, Dultzin et al. 2020, Marziani et al. in preparation).

Negrete et al. (2018) selected much larger sample of xA sources and provided interesting constraints on cosmological parameters. Dultzin et al. 2020 gave very interesting overview on this topic and discuss the perspective of the method based on xA quasars. In this paper we will give an overview on xA sources, and of the techiques used for their search.

2. MAIN SEQUENCES OF UNOBSCURED QUASARS

Basically according to the viewing angle and subsequently according to their fluxes, spectral characteristics - width, shifts and intensities of emission lines, quasars can be divided into two sub-groups - Type 1 or unobscured quasars and Type 2 quasars. But even in the Type 1, quasars differ according to their observational properties (emission line profiles - shifts, widths and intensities, contribution of the iron emission in the spectra, luminosity,...), and also physical characteristics (mass of central black hole, ionization parameter, dimensionless accretion rates, electron density, inclination angle...) (Sulentic et al. 2000). The first sistematization of diverse characteristics of quasars was done by Boroson & Green (1992), using a Principal Component Analysis (PCA) of 87 PG quasars. They noticed that the dominant source of variation in the observed properties is related to a parameter RFe_{II} - intensity ratio between the FeII blend at λ4570 and Hβ (RFe_{II}). The optical plane FWHM(Hβ) and RFe_{II}, can serve to classify quasars along sequence according to systematically-changing properties. This sequence is called Main Sequence of Quasars.

After that time, the number of observed quasars is dramatically increased, but the main sequence has retained its validity (Sulentic et al., 2007; Zamfir et al., 2010; Shen and Ho, 2014; Wolf et al., 2019). According to the width of broad Hβ line it is possible to separate quasars into two populations - pop. A, with FWHM(Hβ) less than 4000 km/s, and pop B. with FWHM(Hβ) higher than this limit (Sulentic et al. 2000). The limit between two populations depends on the luminosity (Marziani et al. 2009). Besides, in the plane RFe_{II}-FWHM(Hβ) data point can be separated into different bins - along RFe_{II} axis into bins, such as A1, A2, A3, etc. (the separation between bins is 0.5 RFe_{II}), and along FWHM(Hβ) axis into A1, B1+, B1++ (4000 km/s is sepation between bins). Each bin represents one spectral type. Quasars within one spectral bin are in similar dynamical and physical conditions.

3. EXTREME ACCRETORS

The subject of our interest are extremely accreting sources, that cover the very end of Main sequence. If the main driver of the quasar sequence is Eddington ratio (Marziani et al, 2001, Shen & Ho, 2014, Bon et al. 2018), it is expected that xA quasars have the strongest contribution of FeII in their optical spectra, and should be the highest radiators, as observationally confirmed. As already mentioned, Marziani & Sulentic (2014) showed that xA quasars radiate at extreme L/L_{Edd}, with very low dispersion ($\sim$ 0.13 dex in the Eddington ratio). This result is consistent with the expectation of accretion disks at very large accretion rates (Abramowicz et al., 1988). Accretion disk theory predicts low radiative efficiency at high accretion rate and that L/L_{Edd} saturates toward a limiting values (Abramowicz et al., 1988; Mineshige et al., 2000; Sadowski et al., 2014). For this reason we use to call them "Eddington standard candles“.

Extreme accretors satisfy three conditions that allow us to use them as "Eddington standard candles“: (i) constant Eddington ratio, (ii) virial motion of low-ionization BLR clouds, and (iii) constant ionization parameter that allows spectral invariance (more details in Dultzin et al. 2020). The condition (ii) permits to express black hole mass by the virial relation, that means that by simple measurements of FWHM of low-ionization lines, we can estimate z-independent accretion luminosity.

xA quasars are little variable in the optical band, and therefore variability is not significantly affecting measurements of Eddington ratio.

3. 1. SELECTION OF EXTREME ACCRETING QUASARS

If we select spectral types along the optical plane of main sequence, satisfying the condition $R_{FeII} \geq 1.0$ (A3, A4, etc.), selected spectra of xA quasars will be characterized with strong FeII emission and Lorentzian Balmer line profiles. They represent around 10% of quasars at low-z ($z \lesssim 0.8$). This simple selection criterion in optical band corresponds to UV selection criteria, mentioned above, based on UV line ratios, and proposed by Marziani & Sulentic (2014): (AlIIIλ1860/SiIII]λ1892 $\geq$ 0.5, and (ii) SiIII]λ1892/CIIIλ1909 $\geq$ 1.0).

To clarify some main properties of extreme accretors, Negrete et al. (2018) identified 334 SDSS quasars on redshift ≤ 0.8, that satisfy criterion $R_{FeII} \geq 1$. They found strong outflow signatures in [OIII], but also in the case of Hβ lines, as a presence of blues-shifted component in the line profile. Since FWHM of Hβ is used as a "virial broadening estimator", the effect of outflow has to be taken into account, in order to estimate a "clear" virial component of the line profile. Besides, authors emphasize a strong effect of the viewing angle on Hβ broadening, that has to be accounted for, in order to bring into agreement the virial luminosity estimates and concordance cosmology.

3. 2. PROBLEMS IN XA SELECTION

Automatic selection of xA quasars using a large databases can be coarseness, and therefore can include spurious xA sources in the set, that can dramatically increase the dispersion in the Hubble diagram of quasars. Negrete et al. (2018) noticed that 32 spectra in their sample have strong contribution of stellar population, which can affect measurements of R_{FeII}. This subsample of objects (hereafter, host galaxy sample) required a different and more carefull approach (Bon et al. 2020, hereafter, Bon20). Spectra were analyzed with the simultaneous multicomponent fit of a host galaxy spectrum, AGN continuum, FeII template and emission lines, using the technique based on ULySS - full spectrum fitting package (Koleva et al. 2009, Bon et al. 2014, Bon et al. 2016). They found that all of the 32 spectra show moderate-to-strong FeII emission and the vast majority strong absorption features in their spectra are typical of evolved stellar populations. The authors emphasized the importance of simultaneous fit in the analysis, because FeII can mimic stellar population spectra (see Figure 1). Namely, in half of the host galaxy sample the stellar population contribution is higher than 40%, and therefore prominent absorption lines of evolved stellar population do mimic FeII emission, so any analysis that does not take into account host galaxy contribution can make mistaken identification of FeII spectral features, overestimate of R_{FeII}, and hence misclassify sources as xA.

From the simultaneous fit results, Bon20 measured the line fluxes, FeII contribution, stellar host contribution, AGN continuum contribution, and some other spectral parameters. This allowed to calculate the mass of the central super-massive black hole (SMBH) using several different methods, as well as an accretion rate. The main problem that pointed out the misclassification of 32 sources was their low L/L_{Edd} (almost all sources have log(L/L_{Edd}) $\leq$ -0.5), which is not in the agreement with expected values for xA sources.

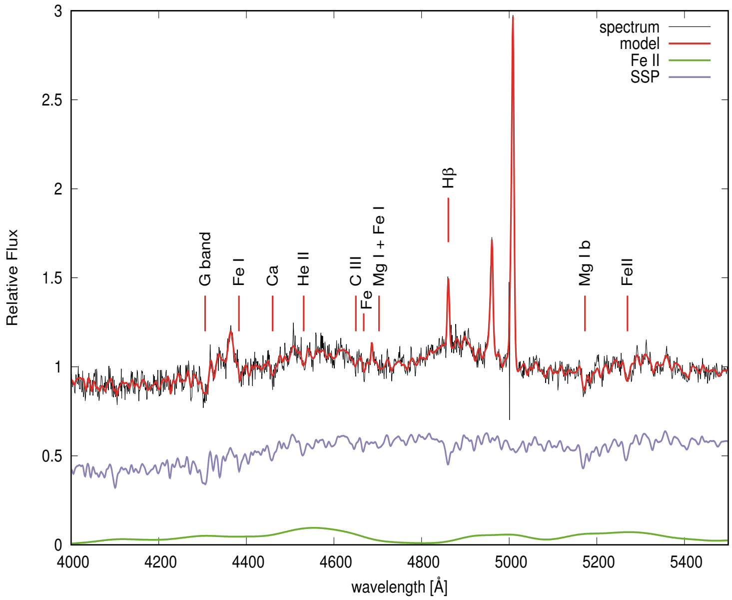

Figure 1: Quasar spectra of SDSS J113651.66+445016.4 where the host galaxy mimic strong FeII emission leading to a mistaken identification of strong FeII emitters. The panel shows (from top to bottom): the real spectra and the best fitting model; single stellar population spectrum that was used in the best fitting model; and the FeII template used in the fit. Some prominent absorption lines are marked on the plot.

The Eddington luminosity is defined by limiting requirement for accretion; the radiation pressure force per particle is equal to the gravitational force. For the case of solar metallicity this implies (see more in Netzer, 2013): $L_{\rm L}/L_{\rm Edd} = 1.5{\times}10^{38} M/M_{\odot}$ erg/s. Therefore, the key point is to determine the $M_{\rm BH}$. Following Vestergaard & Peterson (2006, hereafter, VP06) Bon calculated black hole virial masses with additional constrains for the virial factor as follows:

$$M_{\rm BH} = f\frac{r_{\rm BLR}(\delta v)^2}{G} = f_1(\dot{m}, a) f_2(\theta\,|\,\dot{m})\frac{r_{\rm BLR}(\delta v)^2}{G}, \tag{1}$$

where $r_{\rm BLR}$ is the broad line region size, a is the parameter of a black hole spin, and the broad line virial velocity broadening δv is FWHM of the broad component of Hβ (Negrete et al. 2018). The virial form factor f was assumed to be the product of two terms, one depending on accretion rate and a black hole spin, and another one depending on orientation effects. The dependence on dimensionless accretion rate of f_1 has been parametrized by the $r_{\rm BLR}$ dependence on luminosity (Du et al. 2016). The spin parameter affects the temperature of the accretion disk and hence the SED of the ionizing continuum (Wang et al. 2014).

As the first step Bon20 calculated $M_{\rm BH}$ using Bentz et al. (2013, hereafter B13) correlation between $r_{\rm BLR}$ and optical luminosity, assuming form factor $f = 1$. These results were correlated with the masses obtained from the VP relation. No orientation effects had been considered in both cases.

Typical uncertainties for the $M_{\rm BH}$ are expected to be ≈ 0.3 dex at 1σ (VP06, Marziani et al. 2019), where the main source of uncertainty is most likely due to the combined effect of orientation and Eddington ratio.

The effect of the viewing angle on the Hβ line is assumed to depend on FWHM of the broad Hβ emission line with the relation proposed in Mejia-Restrepo et al. (2018):

$$f_2^{\star} = \left(\frac{\rm FWHM}{4550}\right)^{-1.17}, \tag{2}$$

In addition, we used the correction for $r_{\rm BLR}$ proposed by Martinez-Aldama et al. (2019): $\delta r_{\rm BLR} = \log\,(r_{\rm BLR}/r_{\rm BLR,B13})$, with the $f_2^{\star}$ dependence on FWHM. Then, the correction to $r_{\rm BLR}$ is: $\delta r_{\rm BLR} = (-0.271 \pm 0.030) \log \frac{L_{\rm bol}}{L_{\rm Edd}{}^{\star}} + (-0.396 \pm 0.032)$, where $L_{\rm Edd}{}^{\star}$ means that the Eddington luminosity has been computed with virial mass relation assuming correction $f_2^{\star}$ (Eq. 2).

After the corrections, only one xA candidate (SDSSJ105530.40+132117.7) is recognised as high accretor, with $L/L_{\rm Edd} \approx -0.35$, close to the lower limit for extreme accreting sources.

Another way to estimate $L/L_{\rm Edd}$ can be using the fundamental plane (FP) of accreting black holes (Du et al. 2016), which is based on a correlation between the Eddington ratio, and the observational parameters $R_{\rm FeII}$ and the ratio D between FWHM and velocity dispersion of broad Hβ line ($D = FWHM/\sigma$). The correlation can be written as: $L_{\rm L}/L_{\rm Edd} \approx a + bD + cR_{\rm FeII}$, where a, b, c are coefficients obtained from the fitting of a sample as reported by Du et al. (2016), a=0.31, b=-0.82 and c=0.8. The fundamental plane is consistent with the relations derived from the E1 approach ($L/L_{\rm Edd}$ and $\dot{\mathcal{M}}$ increase as the Hβ profile become narrower [1].).

Spectra from the host galaxy sample appeared to be mainly population B2 and B3, and the shapes of their line profiles were relatively broad, while the $R_{\rm FeII}$ appeared to be relatively high, which according to FP approach lead to overestimated values of Eddington ratio, in comparison to the values obtained by the standard definition of Eddington ratio. In order to investigate the origin of this disagreement, Bon20 reconsidered the fit obtained by Du et al. (2016), due to the possibility of a bias for low $L/L_{\rm Edd}$. The fundamental plane fit of Du et al. (2016) predicts a value of $L/L_{\rm Edd}$ objects almost one order of magnitude systematically higher with respect to the one expected by the distribution of the rest of the objects. We obtained a slightly corrected fit by fitting the residuals with a linear function ($\delta = \log L/L_{\rm Edd} - \log L/L_{\rm Edd}$). A post-correction best fitting line is consistent with $\delta(L/L_{\rm Edd}) \equiv 0$. Applying this correction to the residuals we obtain a slightly modified equation for the fundamental plane log $L/L_{\rm Edd} = \alpha + \beta D + \gamma R_{\rm FeII} \approx 0.774 - 1.33D + 1.30R_{\rm FeII}$. Unfortunately, this new corrected law, do not solve the disagreement between the VP conventional estimates of $L/L_{\rm Edd}$ (see more in Bon20). The disagreement is so large that the highest radiating source in this sample ($L/L_{\rm Edd} \sim 2$) according to the FP has $L/L_{\rm Edd} \approx 0.04$ following VP. This leads to inconsistencies between the main sequence interpretation and spectral type assignment (see, Bon20). Even with the modified FP formula

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[1] As the broad Hβ profile becomes narrower, the line shape changes from Gaussian distribution to Lorentzian, and therefore the parameter D=FWHM/σ tends to 0, since σ bacomes very large. This implies that high $R_{\rm FeII}$ leads to high L/L_{Edd}

with the parameters reported above, the modified FP brings in agreement only several points at the low-$L/L_{\rm Edd}$ end, while the rest of the data remains above the VP estimates by ≈1 dex.

In order to further investigate this discrepancies, Bon20 used the stellar velocity dispersion $\sigma_\star$ of the host, using the scaling law $M_{\rm BH} \approx 1.95 \cdot 10^8\,(\sigma_\star/200)^{5.12}$ $\rm M_\odot$ (McConnell et al. 2011), which is an updated formulation of the original scaling law of Ferrarese & Merritt (2000) and computed $M_{\rm BH}$. The $M_{\rm BH}$ calculated from the VP formula and $M_{\rm BH}$ from host show systematic differences, due to resolution limitations of the SDSS spectra. Bon20 obtained disagreement with measured dispersions when they were lower than twice of the resolution (for SDSS resolution is about 69 km $\rm s^{-1}$), while the results of masses obtained from stellar and VP showed agreement when the host absorption line dispersion was above $\sigma_\star \geq 150$ km $\rm s^{-1}$ (see more in Bon et al. 2020).

Another possibility for this discrepancy is a degeneracy between effects of orientation and $M_{\rm BH}$ in the optical plane of the main sequence. Also, Bon20 could not exclude that B2 and B3 objects contain higher masses of $M_{\rm BH}$. These effects would imply a significant decrease in $L/L_{\rm Edd}$ in the transition from B2 to A2.

After all corrections end tests that Bon20 applied on host galaxy sample, they concluded that all of these objects appears to be low accreting objects, except for only one of them, which could have the value of $L/L_{\rm Edd}$ =0.3.

4. SUMMARY

Extreme accretors represent the sub-class of quasars with almost constant L/L_{Edd}, and therefore might be suitable as Eddington standard candles. The Hubble diagram for xA quasars is consistent with concordance cosmology, and provides better constrain on Ω_M (0.3 ± 0.06) than type Ia supernovae, because of the z ∼ 2 coverage (Dultzin et al. 2020).

In this paper we presented some important techniques needed in the search for high accreting quasars. Multicomponent simultaneous analysis of nebular, stellar and FeII pseudo continuum is important to decrease the possibility to inject some spurious objects that can dramatically increase the dispersion in the Hubble diagram of quasars.

The next step is to select larger sample from the latest data releases of SDSS, that can clarify the main properties of xA quasars.

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