No evidence for an Eddington-ratio dependence of X-ray weakness in BALQSOs

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ABSTRACT

Several works have studied the relation between X-ray, UV, and wind properties in broad absorption line quasars (BALQSOs), generally concluding that the formation of strong winds is tightly connected with the suppression of the ionizing EUV/X-ray emission. The Eddington ratio (λEdd), which measures the accretion rate, is also known to be related with outflow and emission-line properties in the general quasar population. Moreover, models describing quasar accretion depend on λEdd, which can thus possibly affect the relative production of accelerating UV and ionizing EUV/X-ray radiation. In this work, for the first time, we investigated whether BALQSO X-ray properties are related with the Eddington ratio. We selected a sample of 30 BALQSOs with accurate measurements of black-hole mass and BAL properties from the literature, and we complemented it with 4 additional BALQSOs we observed with XMM-Newton to populate the low and high Eddington-ratio regimes. We did not find evidence for a strong relation between λEdd and X-ray suppression, which however shows a significant correlation with the strength of the UV absorption features. These findings are confirmed also by considering a sample of mini-BALQSOs collected from the literature.

Key words: methods: data analysis – galaxies: active – galaxies: nuclei – X-rays: galaxies – quasars: absorption lines

1 INTRODUCTION

One of the most outstanding pieces of evidence for the existence of AGN-driven outflows is the typical broad (> 2000 km s−1) absorption features visible in the UV spectra of Broad Absorption Line QSOs (BALQSOs), which account for ∼ 15% of optically-selected QSOs (e.g. Trump et al. 2006; Gibson et al. 2009a). Such absorption features often have complex structures and are blueshifted with respect to the rest-frame line wavelength, implying outflowing velocities up to ∼ 0.2c (e.g. Rogerson et al. 2016). Less-extreme features (1000−2000 km s−1 in width) are present in optical/UV spectra of the so-called mini-BALQSOs, whose number is comparable to or even greater than the number of BALQSOs, demonstrating the widespread presence of outflows among the whole quasar population (e.g. Ganguly & Brotherton 2008).

The origin of such outflows is thought to be connected to the formation of equatorial winds radiatively driven by UV-line pressure, launched from the accretion disk at ∼ 1016−17 cm (e.g. Proga et al. 2000). The “accretion-disk-wind” model requires the outflowing material not to be over-ionized, as the line-driving efficiency drops when the ionization state of the wind is too high. Several hypotheses have been proposed to avoid such over-ionization, spanning from the presence of shielding material (perhaps a failed wind; e.g. Proga & Kallman 2004) located at the base of the wind that absorbs the EUV/X-ray radiation emitted from the inner regions of the disk, to a high density of the wind itself due to radiation-pressure confinement (e.g. Baskin et al. 2014), to

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occasional intrinsic (i.e. not due to absorption) EUV/X-ray weakness (e.g. Luo et al. 2013, 2014), as predicted by some accretion models during phases of fast accretion (e.g. Meier 2012; Jiang et al. 2018, and references therein).

Some of these scenarios predict an observed X-ray weakness (i.e. a weaker observed X-ray emission than the level expected from the UV luminosity), estimated with the $\Delta \alpha = \alpha_{\text{ox}}(\text{observed}) - \alpha_{\text{ox}}(L_{\text{2500Å}})$ parameter, where $\alpha_{\text{ox}}(\text{observed}) = 0.3838 \times \log(\text{L}_{\text{2500Å}})/L_{\text{ox}}$ is the slope of a power-law connecting the UV at 2500 Å and the observed X-ray at 2 keV. The value of $\alpha_{\text{ox}}$ has been found to correlate with $L_{\text{2500Å}}$ (e.g. Vignali et al. 2003; Strateva et al. 2005; Steffen et al. 2006; Just et al. 2007; Luo et al. 2010) up to $z \approx 6$ (Nanni et al. 2017), and $\alpha_{\text{ox}}(L_{\text{2500Å}})$ is thus the expected value inferred from the UV luminosity. The quantity $\Delta \alpha_{\text{ox}}$ therefore quantifies the deviation of the observed X-ray luminosity with respect to the expectation.

Indeed, BALQSOs have been generally found to be X-ray weak by up to a factor of $\sim 100$ ($\Delta \alpha_{\text{ox}} \sim 0.75$, e.g. Gibson et al. 2009a). To discriminate absorption from intrinsic X-ray weakness as the cause of the observed X-ray weakness, emission in rest-frame hard X-rays, which are not affected by low-to-moderate column densities of absorbing material, must be studied. For instance, Luo et al. (2014) using NuSTAR data found a significant fraction of intrinsically X-ray weak BALQSOs in their local sample. Other authors (e.g. Gallagher et al. 2006; Morabito et al. 2014; Liu et al. 2018) accessed high rest-frame energies using samples of high-redshift (1.4 < $z < 2.9$ ) BALQSOs observed with either Chandra or XMM-Newton. In particular, Morabito et al. (2014) estimated an average intrinsic X-ray weakness of a factor of $\approx 3$ ($\Delta \alpha_{\text{ox}} \approx 0.2$). Recently, Liu et al. (2018) found a fraction of intrinsically X-ray weak BALQSOs of $\approx 6 - 23\%$ among their $z = 1.6 - 2.7$ sample, significantly higher than the $\lesssim 2\%$ fraction of X-ray weak quasars among the general non-BALQSO population (e.g. Gibson et al. 2008). However, results based on X-ray spectral analysis in many cases reveal the presence of X-ray absorption (e.g. Gallagher et al. 2002; Grupe et al. 2003; Shemmer et al. 2005; Giustini et al. 2008). A number of correlations are known between the X-ray weakness and other observational properties of BALQSOs, such as the minimum and maximum velocity of the outflow, and the strength of the absorption features (e.g. Gallagher et al. 2006; Fan et al. 2009; Gibson et al. 2009a; Wu et al. 2010), suggesting that the level of X-ray emission indeed has material effects in shaping the wind observed in the UV.

BALQSOs are generally thought to be powered by fast-accreting SMBHs (e.g. Boroson 2002; Meier 2012), where the accretion rate is measured through the Eddington ratio, defined as $\lambda_{\text{Edd}} = L_{\text{bol}}/L_{\text{Edd}}$, where $L_{\text{Edd}} = 1.26 \times 10^{38} M_{\odot} \text{erg s}^{-1}$. In fact, while BALQSOs have been found to have $\lambda_{\text{Edd}}$ as low as $\approx 0.1$, the fraction of quasars showing BAL features increases with $\lambda_{\text{Edd}}$ (Ganguly et al. 2007). However, as the accretion rate increases, a larger amount of ionizing EUV radiation is produced according to standard accretion models (e.g. Shemmer & Sunyaev 2013). One possibility to avoid overionization of the outflowing material in fast-accreting BALQSOs (i.e. $\lambda_{\text{Edd}} \approx 1$) is that suppression (either intrinsic or due to absorption) of the EUV-to-X-ray emission, responsible for ionization, depends on the Eddington ratio. In this case, one may expect an anti-correlation between $\Delta \alpha_{\text{ox}}$ and $\lambda_{\text{Edd}}$, i.e. a change of the typical observed (and perhaps intrinsic) spectral shape of BALQSOs approaching the Eddington limit. Hints for such a scenario have been derived by, e.g. Luo et al. (2010, 2012) by studying the dependence of $\alpha_{\text{ox}}$ and the quasar bolometric correction on $\lambda_{\text{Edd}}$ (but see also, e.g. Plotkin et al. 2016). From a theoretical point of view, the Shakura & Sunyaev (1973) accretion mode cannot be in place for Eddington ratios exceeding or even approaching unity. Several models have been proposed to describe Eddington-limited accretion flows, some of which predict an intrinsic suppression of X-ray photon production (e.g. Meier 2012; Jiang et al. 2018, and references therein; but see also, e.g. Castelló-Mor et al. 2017). We additionally note that the UV part of quasar SEDs, which is responsible for line-pressure acceleration, may also depend on the accretion rate. Increased UV line pressure may compete against EUV/X-ray ionization in the shaping of quasar wind properties (e.g. Kruczek et al. 2011; Richards et al. 2011), although no significant evidence for a strong variation of the optical/UV part of quasar SEDs for different regimes of $\lambda_{\text{Edd}}$ has been derived observationally (e.g. Scott & Stewart 2014).

The Eddington ratio is considered one of the fundamental parameters driving observable quasar properties (e.g. Shen & Ho 2014), and it is indeed closely related with the quasar “ Eigenvector 1” (e.g. Boroson & Green 1992), i.e. a preferred direction in the quasar multidimensional parameter space along which quasar emission-line properties are aligned. BALQSOs appear to follow the same relations with $\lambda_{\text{Edd}}$ as the overall quasar population (e.g. Yuan & Wills 2003). Moreover, outflow properties (e.g. velocity) in quasars (e.g. Marziani & Sulentic 2012) and, in particular, BALQSOs (e.g. Ganguly et al. 2007) have been found to correlate with $\lambda_{\text{Edd}}$. However, a possible dependence of the X-ray properties of BALQSOs on accretion rate has never been investigated. In this work, we made use of both archival and proposed X-ray observations of a sample of 34 high-redshift (1.5 < $z < 2.2$) SDSS BALQSOs with accurate measurements of black-hole mass to study the dependence of the observed X-ray weakness on Eddington ratio. We used an $H_0 = 70 \text{km s}^{-1} \text{Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_L = 0.7 \Lambda$CDM cosmology.

2 SAMPLE SELECTION AND ANALYSIS

The goal of this work is to study the observed X-ray emission level relative to the UV luminosity, in terms of $\Delta \alpha_{\text{ox}}$, as a function of $\lambda_{\text{Edd}}$ for a sample of high-redshift BALQSOs, where the redshift range (1.5 < $z < 2.2$) was chosen such that both the Mg II and C IV emission lines are included in the SDSS spectral coverage, the former to derive SMBH masses, and the latter to detect the BAL features. By imposing quality cuts on the signal-to-noise ratio (SNR) of the observed SDSS spectra, we limited our study to those objects with securely identified BAL features (i.e. which cannot be ascribed to noisy spectra) and accurate measurements of black-hole mass and BAL properties (i.e. absorption-line strength). In this section, we describe the sample of BALQSOs observed in the X-rays we collected from the literature,

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and the sample of four BALQSOs we observed with XMM-Newton.

2.1 Selection of the BALQSO sample from the literature

Fan et al. (2009), Gibson et al. (2009a), and Morabito et al. (2014) presented the X-ray properties of three samples of 41, 73, and 18 BALQSOs, respectively, for a total of 108 unique objects, covered by Chandra or XMM-Newton observations. We matched them with the catalog of virial black-hole masses and bolometric luminosities for SDSS DRT QSOs of Shen et al. (2011). In order to study a homogeneous sample of objects, representative of the majority of the BALQSO population, and to avoid additional complexity due to different ionization properties of the outflowing material, we considered only objects flagged as high-ionization BALQSOs (HiBALQSOs), thus discarding 9 objects classified as low-ionization BALQSOs (7) or even non-BALQSOs (2) in (Shen et al. 2011, who used more recent SDSS spectra than Gibson et al. 2009a and Fan et al. 2009).

The X-ray emission produced at the base of the jets in radio-detected QSOs is known to be comparable to or even dominant over the disk/corona-linked X-ray emission (e.g. Miller et al. 2011), which is the physical mechanism of interest in this study. An additional X-ray contribution from the jets would thus artificially increase the observed X-ray flux/luminosity leading to biased estimates of $\alpha_{\text{ox}}$ and $\Delta \alpha_{\text{ox}}$. Disentangling the two contributions (corona vs. jets) is a careful spectral analysis, which is prevented by the small number (up to few tens, with a median number of counts of 7) of X-ray counts for the sources considered in this work. Excluding quasars detected in large-area radio surveys from our sample avoids this bias. We therefore discarded 15 radio sources detected in the FIRST radio catalog (White et al. 1997), and 2 QSOs not covered by the FIRST survey, as flagged in Shen et al. (2011), resulting in a parent sample of 82 sources.

Spectral noise can sometimes mimic the absorption features affecting the C IV emission line used to define BALQSOs. In order to select a clean sample of BALQSOs, we imposed a quality cut on the SDSS spectra, requiring a SNR at wavelengths close to the C IV emission line of $\text{SNR}_{\text{CIV}} > 5$ (10 objects discarded). This requirement also ensures an accurate measurement of the Baldwin index (see § 3), an indicator of the absorption strength, which we use later in the analysis together with the Eddington ratio to investigate the dependencies of the X-ray weakness.

The reliability of the Eddington-ratio estimates is strongly dependent on the accuracy of the measured black-hole mass. Single-epoch virial black-hole masses are usually estimated through scaling relations with the FWHM of the Balmer (H$\alpha$ and H$\beta$), Mg II, and C IV emission lines, in order of reliability (see the detailed discussion in Shen 2013; see also, e.g. Shen et al. 2011; Kozlowski 2017). The use of the Balmer emission-line series is precluded to us by the need for spectral coverage of the C IV line, necessary to detect the BAL features. The same absorption lines can affect strongly the shape of the C IV emission lines, and thus the measurement of the FWHM, preventing the use of the C IV emission line to estimate black-hole masses for our sample. We therefore use virial black-hole masses derived from the Mg II emission line consistently for all of our sample. The required simultaneous spectral coverage of the Mg II and C IV lines restricts the redshift range of this work to $1.5 \leq z \leq 2.2$, thus discarding an additional 18 BALQSOs for which Mg II-based black-hole masses are not available.

We finally impose quality cuts on the Mg II line detection ($\text{SNR}_{\text{MgII}} > 5$) and fit ($\chi^2_{\text{MgII}} < 1.2$) to only sources with accurate measurements of black-hole mass, further restricting the sample to 30 BALQSOs. We report in Tab. 1 a summary of the number of sources surviving each of the selection steps, and in Tab. 2 the properties of the final 30 selected sources. Our conclusions below hold if more conservative quality cuts are applied (e.g. $\text{SNR}_{\text{CIV}} > 10$ and $\text{SNR}_{\text{MgII}} > 10$), at the cost of greatly reducing the sample size, as discussed in § 3.

We computed the monochromatic UV luminosities from the flux at (rest-frame) 2500 Å derived by Shen et al. (2011) through spectral fitting, and homogeneously applied the Steffen et al. (2006) calibration, considering $L_{2500\AA}$ as the independent variable:

$$\alpha_{\text{ox}} = -0.137 \times \log L_{2500\AA} + 2.638$$ (1)

Steffen et al. (2006) derived $\alpha_{\text{ox}}(L_{2500\AA})$ for a sample of optically-selected quasars. Since ours is an SDSS-selected sample, we preferred Steffen et al. (2006) over Lusso et al. (2010), who applied an X-ray selection. However, the two calibrations return almost exactly the same results for our sample. We also retrieved the observed luminosities at 2 keV ($L_{2\text{keV}}$) provided by the original works to compute $\alpha_{\text{ox}}$(observed).

Most of the selected BALQSOs are included in the Gibson et al. (2009a) sample, and a few of them are in common with either Fan et al. (2009) or Morabito et al. (2014). Two BALQSO are selected from the Fan et al. (2009) compilation only, while none is included in the Morabito et al. (2014) sample only (see last column of Tab. 2). When X-ray luminosities for a quasar are provided by more than one author, we consistently assumed the value reported by Gibson et al. (2009a), from which the majority of the sample is selected. X-ray luminosities are not corrected for absorption. The general paucity of counts ($\lesssim 80$, with a median value of 7) prevents a detailed spectral analysis, which would be required to estimate with acceptable accuracy the intrinsic luminosities of these sources. In fact, complex absorption models (e.g. with ionized or partially covering absorption) may be suitable descriptions of BALQSO X-ray spectra (e.g. Gallagher et al. 2002), and cannot be well constrained with the available small number of counts.

| Parent sample | 108 |
| HiBAL | 99 |
| Radio undetected | 82 |
| $\text{SNR}_{\text{CIV}} > 5$ | 72 |
| Spectral coverage of Mg II | 54 |
| $\text{SNR}_{\text{MgII}} > 5$ and $\chi^2_{\text{MgII}} < 1.2$ | 30 |
Fig. 1 presents the observed X-ray weakness as a function of Eddington ratio for these 30 sources as circles. A Spearman’s ρ test and a generalized Kendall’s τ test returns a probability in favor of a correlation between Δα and λedd of 0.9977 and 0.9983, respectively. These values are a hint for a possible correlation, but the sample does not populate the extreme tails of the Eddington-ratio distribution; i.e. λedd ≲ 0.1 and, especially, λedd ≈ 1, preventing an accurate assessment of a possible relation.

True uncertainties on the estimated black-hole masses are due to a complex combination of factors, like the measurement of the line profile and width, and the continuum luminosity. Shen et al. (2011) report errors on black-hole masses which include these observational measurement errors. However, the dominant uncertainty factor is the scatter of the calibration between black-hole mass and Mg II line width, which is ≈ 0.35 dex (e.g. Shen et al. 2011). In Fig. 1 we use this value to estimate the uncertainty on λedd. We also show the median error on Δα derived from the statistical uncertainties on the X-ray counts only. We note that the non-parametric statistical tests we used are based on point ranking, and thus are not nominally sensitive to the error bars, although their statistical power decreases in the case of large uncertainties.

2.2 Selection of our XMM-Newton targets, data reduction and analysis

In order to increase the number of BALQSOs with low and high values of Eddington ratio, thus allowing us to determine with high significance if the Δα-λedd correlation exists, during AO16 we obtained XMM-Newton observations of four BALQSOs (see Tab. 3). They were selected among the BALQSOs included in the Gibson et al. (2009a) catalog with black-hole mass from Shen et al. (2011) satisfying the quality cuts described in § 2.1, with the additional requirement to have \( \log \lambda_{edd} \approx 1 \) or \( \log \lambda_{edd} \approx 0.1 \) to sample better these accretion regimes (see Tab. 2). X-ray data were reduced and analyzed following standard SAS procedures. Periods of high background levels (count rates > 0.4 cts s\(^{-1}\) for the PN camera and > 0.35 cts s\(^{-1}\) for the MOS cameras) were filtered out. Tab. 3 reports the filtered exposure times. Our sources have ≈ 160 – 2000 net counts in the 0.5 – 10 keV band, considering the three XMM-Newton cameras.

To be consistent with the derivation of the observed X-ray weakness in Gibson et al. (2009a), and also to avoid making strong assumptions about the X-ray spectra (e.g. neutral absorption), we performed a spectral analysis assuming a broken power-law model (\( wabs \times bknpowerlaw \) in XSPEC), with break energy fixed at rest-frame 2 keV. Best-fitting parameters are reported in Tab. 4. For J164452.70+430752.20 we could not constrain the low-energy photon index, which hit the hard low boundary of the allowed parameter range (i.e. \( \Gamma = -3 \)). We therefore fixed it to that value, which hints at a significant level of absorption. X-ray monochromatic luminosities are derived as observed (i.e. no correction for absorption has been applied), similarly to Gibson et al. (2009a). Hereafter, we will use these observed values (squares in Fig. 1) for consistency with the sample collected from the literature. The utilized model describes the effective (i.e. observed) shape of the X-ray spectrum, and the resulting observed luminosities are thus not strongly dependent on the true intrinsic spectral parameters (e.g. photon index and column density, which for low-to-moderate numbers of counts are strongly degenerate), nor the physical state of the possible absorbing material (e.g. neutral vs. partly ionized).

2.2.1 Estimating the intrinsic luminosity

The number of net counts we detected for our targets (see last two columns of Tab. 3) allowed us to perform a simple spectral analysis assuming a power-law model with both Galactic and intrinsic neutral absorption (model \( wabs \times zwabs \times powerlaw \) in XSPEC\(^3\)) to estimate their intrinsic photon indices \( \Gamma \), column densities, and luminosities. Best-fitting parameters are reported in Tab. 5. The best-fitting photon indices for two sources are flatter than the common values found for quasars, probably due to their photon counting statistics (≈ 160 – 230 net counts, see Tab. 3) not being sufficiently high to break the degeneracy between (likely complex) absorption and flat photon index. For these objects we repeated the fit fixing the photon indices to \( \Gamma = 1.9 \). Tab. 5 reports also the intrinsic (i.e. absorption-corrected) X-ray monochromatic luminosities, used to compute the Δα values, which are thus estimates of the intrinsic X-ray weakness. We note that J164452.70+430752.20 shows the largest intrinsic column density in the sample, as expected from its very hard effective spectrum (see previous section).

We stress that here we make a strong assumption considering the obscuring material neutral and fully covering, and thus for the rest of the analysis, consistently with the sample selected from the literature, we use the observed luminosities and Δα values derived from the broken power-law model in the previous section. As expected, since here we apply a correction for absorption, the luminosities and Δα values reported in Tab. 5 are slightly higher than the observed values (Tab. 4), although the difference is smaller than the typical Δα uncertainties. Therefore, the use of observed or intrinsic luminosities for our four sources does not affect significantly the results.

3 RESULTS AND DISCUSSION

In § 3.1 we describe the results of our investigation of a putative anti-correlation between Δα and λedd. In § 3.2 we study the relation between Eddington ratio and BAL strength, as parametrized by the balnicity index. In § 3.3 we include in our investigation a sample of mini-BALQSOs that satisfy our selection requirements, in order to expand the analysis to objects with weaker absorption features. Finally, in § 3.4 we discuss and interpret the results.

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\(^1\) We used the ASURV v1.2 package (http://www.astrostatistics.psu.edu/statcodes/sc_censor.html), which accounts for censored data.

\(^2\) https://www.cosmos.esa.int/web/xmm-newton/sas-threads

\(^3\) heasarc.gsfc.nasa.gov/xanadu/xspec/
Table 2. Main properties of the sample of BALQSOs selected from the literature and BALQSOs newly observed in X-rays.

| SDSS ID       | $z$ | log($L_{bol}$) | log($M_{BH}/M_\odot$) | log($\lambda_{Edd}$) | $\Delta \alpha_{ox}$ | $\mu_0$ | Ref.      |
|---------------|-----|----------------|-------------------------|----------------------|--------------------|--------|-----------|
| 011227.60−011221.7 | 1.76 | 47.60 | 9.51 | −0.60 | −0.70 | 2150 | G09     |
| 020230.66−075341.2 | 1.72 | 46.60 | 9.12 | −0.62 | < −0.24 | 208 | F09     |
| 024304.68+000005.4 | 1.99 | 46.95 | 9.70 | −0.85 | < −0.10 | 325 | G09, G09 |
| 083104.90+532500.1 | 2.07 | 47.40 | 10.00 | −0.70 | < −0.51 | 556 | G09     |
| 084533.66+340243.6 | 2.15 | 47.59 | 10.27 | −0.79 | < −0.18 | 2638 | G09     |
| 092138.44+301546.9 | 1.50 | 46.85 | 9.34 | −0.59 | < −0.51 | 1 | F09, G09 |
| 095341.47+033545.7 | 1.82 | 47.54 | 9.35 | +0.09 | −0.38 | 5 | G09, M14 |
| 094300.55+481140.5 | 1.81 | 46.77 | 9.17 | −0.50 | < −0.33 | 52.2 | G09,F09 |
| 094440.42+041055.6 | 1.98 | 46.71 | 8.88 | −0.27 | < −0.34 | 1104 | F09     |
| 095944.47+051518.3 | 1.60 | 46.52 | 9.71 | −1.29 | −0.15 | 130 | G09     |
| 100711.80+053208.9 | 2.10 | 47.81 | 10.43 | −0.72 | −0.27 | 4263 | G09, M14 |
| 110637.15+522233.3 | 1.84 | 46.58 | 9.33 | −0.85 | −0.26 | 588.0 | G09     |
| 120522.18+433140.4 | 1.92 | 46.63 | 9.42 | −0.99 | < −0.23 | 1659 | G09, G09 |
| 120626.17+151335.5 | 1.63 | 46.79 | 9.30 | −0.61 | −0.47 | 1429 | G09     |
| 121125.48+151851.5 | 1.96 | 46.75 | 9.45 | −0.80 | −0.41 | 5137 | G09     |
| 121440.27+142559.1 | 1.62 | 47.14 | 9.37 | −0.33 | < −0.62 | 3301 | G09     |
| 121950.95+104700.0 | 1.62 | 46.99 | 9.31 | −0.45 | < −0.49 | 3288 | G09     |
| 122637.02+013016.0 | 1.55 | 46.86 | 9.38 | −0.82 | < −0.27 | 3159 | G09     |
| 130136.12+000157.9 | 1.78 | 47.16 | 9.83 | −0.77 | −0.42 | 4522 | G09     |
| 142620.30+351712.1 | 1.75 | 46.7 | 9.31 | −0.71 | 0.02 | 245.2 | G09     |
| 142640.83+322158.7 | 1.54 | 46.39 | 9.36 | −1.12 | −0.31 | 101.5 | G09     |
| 142654.94+375359.9 | 1.81 | 46.54 | 9.56 | −1.13 | −0.26 | 239.5 | G09,F09 |
| 143031.78+221459.5 | 2.21 | 46.46 | 9.6 | −1.24 | < 0.16 | 308.8 | G09     |
| 143117.93+364705.9 | 2.1 | 46.84 | 9.42 | −0.68 | −0.05 | 426.1 | G09     |
| 143411.23+330015.3 | 1.79 | 46.48 | 9.5 | −1.12 | −0.03 | 70.7 | G09     |
| 143511.96+483140.2 | 1.89 | 46.74 | 9.62 | −0.98 | 0.01 | 314.2 | G09     |
| 143752.75+024854.5 | 1.92 | 47.05 | 9.97 | −1.02 | < −0.42 | 2663 | G09, M14 |
| 143853.36+354918.7 | 1.55 | 46.51 | 9.04 | −0.63 | < −0.14 | 1079 | G09     |
| 155338.20+551401.9 | 1.64 | 46.72 | 9.69 | −1.07 | −0.22 | 18 | G09     |
| 235253.51−002850.4 | 1.62 | 46.83 | 9.35 | −0.62 | < −0.82 | 4307 | G09     |

Newly observed sources

| SDSS ID       | $z$ | log($L_{bol}$) | log($M_{BH}/M_\odot$) | log($\lambda_{Edd}$) | $\Delta \alpha_{ox}$ | $\mu_0$ | Ref.      |
|---------------|-----|----------------|-------------------------|----------------------|--------------------|--------|-----------|
| 0938+3805     | 1.828 | 47.51 | 9.4 | 0.01 | −0.08 | 167 | This work |
| 1112+0055     | 1.687 | 47.07 | 10.2 | −1.22 | −0.09 | 440 | This work |
| 1252+0527     | 1.900 | 47.42 | 9.5 | −0.21 | 0.12 | 95 | This work |
| 1644+4307     | 1.715 | 47.28 | 10.1 | −0.96 | −0.14 | 85 | This work |

3.1 $\Delta \alpha_{ox}$ versus $\lambda_{Edd}$

Adding our targets with low and high Eddington ratios to the putative $\Delta \alpha_{ox} - \lambda_{Edd}$ anti-correlation. In fact, the probability of a correlation decreases to 0.966 and 0.982 according to Spearman’s $\rho$ and Kendall’s $\tau$ tests, respectively. This is largely due to the two sources with $\lambda_{Edd} \approx 1$ showing a level of X-ray emission close to expectation (i.e. $\Delta \alpha_{ox} = 0$) and much higher than other BALQSOs with similar or slightly lower $\lambda_{Edd}$. We therefore conclude that there is no clear and
simple dependence of X-ray weakness on Eddington ratio in BALQSOs.

Table 4. Best-fitting spectral parameters assuming a broken power-law emission. The luminosity at rest-frame 2 keV is observed (i.e. not corrected for absorption).

| SDSS ID          | Γ1    | Γ2   | $F_{0.5-2\text{keV}}$ | $L_{2-10\text{keV}}$ | $L_{0.5-2\text{keV}}$ | $\Delta\alpha_{ox}$ |
|------------------|-------|------|-----------------------|-----------------------|-----------------------|---------------------|
| 093846.80+380549.8 | $-0.91^{+0.70}_{-0.61}$ | $1.63^{+0.08}_{-0.05}$ | 3.50                  | 1.22                  | $-0.08$              |
| 111249.70+005310.10 | $0.67^{+0.22}_{-0.21}$ | $1.80^{+0.27}_{-0.05}$ | 2.36                  | 0.61                  | $-0.09$              |
| 125216.60+052737.70 | $2.06^{+0.22}_{-0.18}$ | $2.11^{+0.05}_{-0.05}$ | 7.80                  | 3.48                  | 0.12                 |
| 164452.70+430752.20 | $-3.00$ fixed | $1.25^{+0.15}_{-0.09}$ | 2.29                  | 0.62                  | $-0.14$              |

Table 5. Best-fitting spectral parameters assuming power-law emission absorbed by neutral material. Luminosities are intrinsic.

| SDSS ID          | Γ    | $N_H$ | $F_{0.5-2\text{keV}}$ | $L_{2-10\text{keV}}$ | $L_{0.5-2\text{keV}}$ | $\Delta\alpha_{ox}$ |
|------------------|------|-------|-----------------------|-----------------------|-----------------------|---------------------|
| 093846.80+380549.8 | $1.90^{+0.13}_{-0.13}$ | $1.4^{+0.3}_{-0.4}$ | 3.59                  | 1.51                  | 1.81                  | $-0.01$             |
| 111249.70+005310.10 | $1.39^{+0.15}_{-0.15}$ | $0.7^{+0.6}_{-0.4}$  | 2.35                  | 0.96                  | 0.73                  | $-0.06$             |
| 125216.60+052737.70 | $1.90$ fixed | $2.2^{+0.5}_{-0.5}$  | 2.60                  | 1.14                  | 1.35                  | 0.04               |
| 164452.70+430752.20 | $1.67^{+0.05}_{-0.21}$ | $2.4^{+0.1}_{-0.3}$  | 2.32                  | 1.11                  | 1.04                  | $-0.05$             |

3.2 $\Delta\alpha_{ox}$ versus BAL strength

Several authors have investigated correlations between $\Delta\alpha_{ox}$ and the physical parameters of the outflow in BALQSOs, including the outflow velocity and absorption equivalent width (e.g. Gallagher et al. 2006; Gibson et al. 2009a; Wu et al. 2010), finding that $\Delta\alpha_{ox}$ is more negative in BALQSOs with stronger absorption features. We therefore investigated whether our targets follow this trend, and if the Eddington ratio plays a secondary role in driving the X-ray weakness. As a measure of BAL strength, we used the extended balnicity index ($BI_0$), defined by Gibson et al. (2009a) as

$$BI_0 = \int_0^{25000} (1 - \frac{f_v}{0.9}) C \, dv,$$

where $f_v$ is the ratio of the observed spectrum to the continuum model as a function of the velocity $v$, and $C$ is a constant set to unity if the spectrum is at least 10% below the continuum model for velocity widths of at least 2000 km s$^{-1}$ and zero otherwise.

Following Gibson et al. (2009a), BALQSOs have $BI_0 > 0$ km s$^{-1}$. We collected the values of $BI_0$ for our sample from Gibson et al. (2009a). Symbols in Fig. 1 are color coded according to their balnicity index ($BI_0$; see § 3). The horizontal dashed line marks the locus of quasars with normal levels of X-ray emission (i.e. $\Delta\alpha_{ox} = 0$). The median uncertainties are shown as grey error bars in the bottom-right corner of the plot, and account only for the dominant error factors; i.e. the scatter in the $MBH$ $-$ $FWHM_{\text{MgII}}$ ($\approx 0.35$ dex; e.g. Shen et al. 2011) relation for $\lambda_{Edd}$, and the statistical uncertainties on the X-ray counts for $\Delta\alpha_{ox}$. 

Following Gibson et al. (2009a), BALQSOs have $BI_0 > 0$ km s$^{-1}$. We collected the values of $BI_0$ for our sample from Gibson et al. (2009a). Symbols in Fig. 1 are color coded according to their balnicity index. Fig. 2 presents the X-ray weakness as a function of $BI_0$. Objects in our sample with strong BAL features ($BI_0 > 1000$ km s$^{-1}$) are indeed typically X-ray weak ($-\Delta\alpha_{ox} = 0.2–0.8$). Sources with lower values of $BI_0$ show a large scatter of X-ray weakness. Gibson et al. (2009a) do not report uncertainties on $BI_0$, which are dominated by the continuum emission measurement. We estimated its uncertainty from Filiz Ak et al. (2013), who studied a subsample of Gibson et al. (2009a), and used the median value to approximate the uncertainties on $BI_0$ in Fig. 2.
We used a 10% uncertainty for are shown as grey error bars in the bottom-right corner of the plot.

3.3 Expanding the sample to mini-BALQSOs

Our four targets happened to have quite weak BALs, as its dominant factor of uncertainty. The horizontal dashed line marks the locus of quasars with normal $\text{BI}$ levels of X-ray emission (i.e. $\Delta \alpha_\text{ox} = 0$). The median uncertainties are shown as grey error bars in the bottom-right corner of the plot. We used a 10% uncertainty for $B_{\text{I}_{\alpha}}$ (e.g. Filiz Ak et al. 2013), and the statistical uncertainties on the X-ray counts for $\Delta \alpha_\text{ox}$, which is its dominant factor of uncertainty.

3.4 Discussion

According to Fig. 2 and the statistical tests run in the previous section, prominent BAL features are good proxies of X-ray weakness in BALQSOs, irrespective of their Eddington ratio. While the fraction of BALQSOs appears to depend on the Eddington ratio (e.g. Ganguly et al. 2007), the lack of a clear correlation between $\Delta \alpha_\text{ox}$ and $\lambda_{\text{Edd}}$ suggests that the observable X-ray-to-UV relative emission does not depend on the accretion rate. Since the optical/UV SEDs of quasars do not show evidence for a strong variation with Eddington ratio (e.g. Scott & Stewart 2014), this means that also the X-ray part of the SED does not vary strongly, at least for optically selected BALQSOs. Our entire sample of 34 BALQSOs spans a relatively narrow range of luminosity ($46.3 \leq \log \lambda_{\text{Edd}} \leq 47.8$; see Tab. 2), and thus we do not expect strong evolution in luminosity to affect this result.

We note that sources with strong BAL features ($B_{\text{I}_{\alpha}} > 1000 \text{ km s}^{-1}$) show a hint of an anti-correlation between $\Delta \alpha_\text{ox}$ and $\lambda_{\text{Edd}}$: the Spearman’s $\rho$ test and the generalized Kendall’s $\tau$ test return a probability of anti-correlation of $0.94$ and $0.96$, respectively, considering only the 14 BALQSOs with $B_{\text{I}_{\alpha}} > 1000 \text{ km s}^{-1}$, although the small sample size and the narrow $\lambda_{\text{Edd}}$ regime ($-1 \leq \log \lambda_{\text{Edd}} \leq -0.4$) spanned prevents us from drawing solid conclusions. Most of the scatter in Fig. 1 is indeed due to BALQSOs with low $B_{\text{I}_{\alpha}}$. We speculate that the putative anti-correlation may thus be in place for BALQSOs with powerful and efficient outflows. To check this hypothesis, larger samples of BALQSOs with strong BAL features and accurate measurements of SMBH mass must be observed in X-rays. Weaker and less-massive winds may instead be present even if the X-ray emission is not significantly suppressed along the line of sight (see also, e.g. Gibson et al. 2009b; Hamann et al. 2013). For instance, stochastic events, such as a local overdensity of the disk or the intervening of a dense gas cloud, may provide the needed screening against the ionizing radiation to locally allow the acceleration of a wind, which would thus be detected through absorption features much weaker than in the case of global, massive outflows, but would not cause significant X-ray absorption along the line of sight.

In order to check if our results are sensitive to the particular quality cuts we imposed in § 2.1, we repeated the analysis with a more conservative selection requiring $SNR_{\text{H} \alpha} > 10$ and $SNR_{\text{C IV}} > 10$. This conservative sample consists of 19 BALQSOs, including our 4 newly observed sources. The results hold, although with lower significance, due to the smaller sample size.

Finally, we note that the observed scatter of any intrinsic relation can be increased by orientation effects. In fact, orientation is known to play a non-negligible role in the determination of physical properties of quasars (e.g. Jarvis & McLure 2006; Shen & Ho 2014), and, in particular, of black-hole virial mass estimates (e.g. Runnoe et al. 2013). Similarly, observational properties of BALQSOs, such as the strength and velocity of the absorption features, may differ along different lines of sight (e.g. Filiz Ak et al. 2014).

Figure 2. Observed X-ray weakness ($\Delta \alpha_\text{ox}$) as a function of $B_{\text{I}_{\alpha}}$. Symbols are the same as in Fig. 1 and are color-coded according to their Eddington ratio. The $x$-axis is in logarithmic units for visual purposes. Mini-BALQSOs (which have $B_{\text{I}_{\alpha}} = 0 \text{ km s}^{-1}$ by definition) and BALQSOs with $B_{\text{I}_{\alpha}} < 10 \text{ km s}^{-1}$ are plotted as upper limits on $B_{\text{I}_{\alpha}}$ (symbols with leftward-pointing arrows). The horizontal dashed line marks the locus of quasars with normal levels of X-ray emission (i.e. $\Delta \alpha_\text{ox} = 0$). The median uncertainties are shown as grey error bars in the bottom-right corner of the plot.
We investigated the existence of a possible relation between the observed X-ray weakness ($\Delta\alpha_{\text{ox}}$) and the Eddington ratio $\lambda_{\text{Edd}}$ in a sample of 34 BALQSOs. Such a trend could help alleviate the overionization of outflowing material necessary to produce a disk wind, if line-driven radiation pressure is the main accelerating mechanism. Moreover, both theoretical and observational findings suggest a change of the level of X-ray production in quasars approaching the Eddington limit. However, we did not find evidence for a strong anti-correlation between $\Delta\alpha_{\text{ox}}$ and $\lambda_{\text{Edd}}$. Instead, the strength of the BAL features appears to be a better tracer of $\Delta\alpha_{\text{ox}}$ than the Eddington ratio. Our results are confirmed also by considering a sample of mini-BALQSOs collected from the literature. Future X-ray observations of larger samples of BALQSOs with strong absorption features and accurate measurements of black-hole mass are needed to check if the anti-correlation between $\Delta\alpha_{\text{ox}}$ and $\lambda_{\text{Edd}}$ is in place at least in the subpopulation with strong and massive winds, for which a stronger suppression of the X-ray emission may be required to accelerate the outflows efficiently.

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REFERENCES

Arnaud K. A., 1996, in Jacoby G. H., Barnes J., eds, Astronomical Society of the Pacific Conference Series Vol. 101, Astronomical Data Analysis Software and Systems V. p. 17
Baskin A., Laor A., Stern J., 2014, MNRAS, 445, 3025
Boroson T. A., 2002, ApJ, 565, 78
Boroson T. A., Green R. F., 1992, ApJS, 80, 109
Castelló-Mor N., et al., 2017, MNRAS, 467, 1299
Fan L. L., Wang H. Y., Wang T., Dong X., Zhang K., Cheng F., 2009, ApJ, 690, 1006
Filiz Ak N., et al., 2013, ApJ, 777, 168
Filiz Ak N., et al., 2014, ApJ, 791, 88
Gallagher S. C., Brandt W. N., Chartas G., Garmire G. P., 2002, ApJ, 567, 37
Gallagher S. C., Brandt W. N., Chartas G., Priddey R., Garmire G. P., Sambruna R. M., 2006, ApJ, 644, 709
Ganguly R., Brotherton M. S., 2008, ApJ, 672, 102
Ganguly R., Brotherton M. S., Cales S., Scoggins B., Shang Z., Vestergaard M., 2007, ApJ, 665, 990
Gibson R. R., Brandt W. N., Schneider D. P., 2008, ApJ, 685, 773
Gibson R. R., et al., 2009a, ApJ, 692, 758
Gibson R. R., Brandt W. N., Gallagher S. C., Schneider D. P., 2009b, ApJ, 696, 924
Giustini M., Cappi M., Vignali C., 2008, A&A, 491, 425
Grupe D., Mathur S., Elvis M., 2003, AJ, 126, 1159
Hamann F., Chartas G., McGraw S., Rodriguez Hidalgo P., Shields J., Capellupo D., Charlton J., Eracleous M., 2013, MNRAS, 435, 133
Jarvis M. J., McLure R. J., 2006, MNRAS, 369, 182
Jiang Y.-F., Stone J., Davis S. W., 2018, preprint, (arXiv:1709.02845)
Just D. W., Brandt W. N., Shemmer O., Steffen A. T., Schneider D. P., Chartas G., Garmire G. P., 2007, ApJ, 665, 1004
Kozlowski S., 2017, ApJS, 228, 9
Kruczek N. E., et al., 2011, AJ, 142, 130
Liu H., Luo B., Brandt W. N., Gallagher S. C., Garmire G. P., 2018, preprint, (arXiv:1804.05704)
Luo B., et al., 2013, ApJ, 772, 153
Luo B., et al., 2014, ApJ, 794, 70
Lusso E., et al., 2010, A&A, 512, A34
Lusso E., et al., 2012, MNRAS, 425, 623
Marziani P., Sulentic J. W., 2012, The Astronomical Review, 7, 33
Meier D. L., 2012, Black Hole Astrophysics: The Engine Paradigm
Miller B. P., Brandt W. N., Schneider D. P., Gibson R. R., Steffen A. T., Wu J., 2011, ApJ, 726, 20
Morabito L. K., Dai X., Leighly K. M., Sivakoff G. R., Shankar F., 2014, ApJ, 786, 58
Nanni R., Vignali C., Gilli R., Moretti A., Brandt W. N., 2017, preprint, (arXiv:1704.08693)
Plotkin R. M., Gallo E., Haardt F., Miller B. P., Wood C. J. L., Reines A. E., Wu J., Greene J. E., 2016, ApJ, 825, 139
Proga D., Kallman T. R., 2004, ApJ, 616, 688
Proga D., Stone J. M., Kallman T. R., 2000, ApJ, 543, 686
Richards G. T., et al., 2011, AJ, 141, 167
Rogerson J. A., Hall P. B., Rodríguez Hidalgo P., Pirkola P., Brandt W. N., Filiz Ak N., 2016, MNRAS, 457, 405
Runnoe J. C., Brotherton M. S., Shang Z., Wills B. J., DiPompeo M. A., 2013, MNRAS, 429, 135
Scott A. E., Stewart G. C., 2014, MNRAS, 438, 2253
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337
Shemmer O., Brandt W. N., Vignali C., Schneider D. P., Fan X., Richards G. T., Strauss M. A., 2005, ApJ, 639, 729
Shen Y., 2013, Bulletin of the Astronomical Society of India, 41, 61
Shen Y., Ho L. C., 2014, Nature, 513, 210
Shen Y., et al., 2011, ApJS, 194, 45
Steffen A. T., Strateva I., Brandt W. N., Alexander D. M., Koekestra A. M., Lehmer B. D., Schneider D. P., Vignali C., 2006, ApJ, 642, 88
Strateva I. V., Brandt W. N., Vanden Berk D. G., Vignali C., 2005, AJ, 130, 387
Trump J. R., et al., 2006, ApJS, 165, 2
Vignali C., Brandt W. N., Schneider D. P., 2003, AJ, 125, 433
Weisskopf M. C., Wu K., Trimble V., O’Dell S. L., Elsner R. F., Zavlin V. E., Kouveliotou C., 2007, ApJ, 657, 1026
White R. L., Becker R. H., Helfand D. J., Gregg M. D., 1997, ApJ, 475, 479
Wu J., Brandt W. N., Comins M. L., Gibson R. R., Shemmer O., Garmire G. P., Schneider D. P., 2010, ApJ, 724, 762
Yuan M. J., Wills B. J., 2003, ApJ, 593, L11

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