Review

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Measures of the Soft X-ray Excess as an Eigenvector 1 Parameter for Active Galactic Nuclei

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Abstract. We present a preliminary analysis of X-ray data of quasars in the context of the 4D eigenvector 1 parameter space (Sulentic *et al.* 2000a, b). 4DE1 serves as a surrogate H-R diagram for representing empirical diversity among quasars and identifying the physical drivers of the diversity. The soft X-ray spectral index ($\Gamma_{\rm soft}$) was adopted as one of the key 4DE1 that correlates contrasting extremes in Type 1 properties. 4DE1 motivated the hypothesis of two quasar populations (A and B) divided by $L/L_{\rm EDD} \approx 0.2$. Pop. A is a largely radio-quiet population with FWHM $H\beta < 4000$ km/s and often showing a soft X-ray excess. Pop. B is a mix of radio-quiet and a majority of RL quasars shows only a hard X-ray power-law SED. The X-ray separation was based upon earlier ROSAT and ASCA data but we now confirm this dichotomy with large samples of X-ray spectra obtained with XMM-Newton and SWIFT. One popular idea connects the soft excess in Pop. A quasars as a signature of thermal emission from a hot accretion disk in sources radiating close to the Eddington limit.

Key words. Galaxies: active—quasars—emission lines—X-rays.

1. Introduction

The 4D eigenvector 1 parameter space was introduced in 2000 (Sulentic *et al.* 2000a, b) as a surrogate H-R diagram for Type 1 AGN. It was intended to fill the need for a context within which one could compare and contrast quasars and Seyfert 1 galaxies. The approach was motivated by previous studies in optical (Boroson & Green 1992), UV (Gaskell 1982) and X-ray (Wang *et al.* 1996) spectra. Four parameters were proposed as best contrasting extremes in Type 1 QSOs properties and this motivated the hypothesis of two quasar populations A and B as either extremes along a quasar 'main sequence' or possibly two physically distinct quasar classes – a dichotomy encompassing the radio-quiet vs. radio-loud debate (Zamfir *et al.* 2008). In this context, population A and B quasars are different in almost every multi-wavelength measure. Differences appear to be driven primarily by source Eddington ratio (proportional to accretion rate) the most effective population separation at $L/L_{\mathrm{Edd}} = 0.2 \pm 0.1$ for $\log MBH \sim 8.0$ (Marziani *et al.* 2001).

Four key parameters were adopted for both practical as well as physical reasons. They involve measures of: (1) FWHM Hβ (MgII for high z QSOs), (2) RFeII, flux or equivalent width (EW) ratio of the optical FeII λ4570 Å blue blend and the broad component of Hβ, (3) velocity shift at FWHM for high ionization line (HIL) CIV λ1549 Å and (4) soft X-ray photon index (Γ_{soft}). The first two measures were stimulated by the PG quasar survey which revealed considerable spectroscopic diversity in a small sample of low z sources. At the same time, ROSAT data suggested that these two measures correlated well with the soft-Xray excess. Even earlier a systematic CIV blueshift had been found in some quasars, and by 2006 the HST archive provided good UV spectra of the CIV region for almost 140 sources. The study carried out by Sulentic *et al.* (2007) addressed inter alia the problem of spectroscopic discrimination of the A and B populations. It involved the expanded sample of all low z quasars with HST/FOS UV spectra which allow to measure the CIV λ1549 Å. The study showed that profile shift at half-maximum of CIV λ1549 Å line constitutes the UV eigenvector 1 measurement in the 4DE1 parameter space.

After the introduction of Γ_{soft} in 2000, not much new X-ray data became available until the advent of XMM-Newton which now provides spectra covering the 0.5–10 keV range for a large number of low z Type 1 sources. Sulentic *et al.* (2008) provided evidence that sources with a soft X-ray excess were concentrated among high accreting population A quasars while population B sources tended to show only a hard power-law. The soft X-ray excess, first mentioned by Singh *et al.* (1985) is a dominant component of the X-ray spectra of many AGN. The excess detected in soft X-rays, below 2 keV, is usually interpreted as a measure of thermal emission connected with the accretion disk (Grupe *et al.* 2004; Mineshige *et al.* 2000). Therefore it is expected that the sources with higher accretion rates show a stronger excess in their soft X-ray spectra.

Fitting a simple power-law to high accretion rate QSOs shows a steeper X-ray spectrum that can be represented by high values of spectral index Γ (Grupe *et al.* 2004; Wang *et al.* 1996; Boller *et al.* 1996; Sulentic *et al.* 2000a, b, 2008). We based our study on XMM archival spectra. We report here on a new statistical analysis of spectral indices of 250+ Type 1 QSOs in the 4DE1 context which confirms the Pop. A–B difference previously reported.

In section 2, we present the sample and data used in this study. Section 3 contains a statistical analysis of the sample and section 4 presents the main conclusions.

2. Sample selection

2.1 *X-ray data*

Our sample includes all Type 1 quasars with accurate measurements of emission lines included in the 4DE1 optical scheme and with $z < 0.8$. We study population A and population B in the terms of the soft X-ray excess. This work is based on data from two X-ray observatories: XMM-Newton (XMM) and Swift.

We used the XMM-Newton database, XMMFITCAT: The XMM-Newton spectral-fit database (Corral *et al.* 2015) provides us with information about the spectral slope for sources observed with the EPIC pn and MOS instruments. XMM-FITCAT provides results of fitting XMM-Newton spectra with six models. For this study, we adopted values of photon indices (Γ) derived from fits using the absorbed power-law model. The fits were performed by Corral *et al.* (2015) in three bands: 0.5–2 keV ($\Gamma_{\rm soft}$), 2–10 keV ($\Gamma_{\rm hard}$) and 0.5–10 keV ($\Gamma_{\rm full}$). Γ were derived in the XMMFITCAT catalog for spectra for which number of source counts collected is >50 counts. We selected from the catalog the sources with good fit according to Corral *et al.* (2015).

In order to provide spectral information from SWIFT, we used the values of gamma obtained from fitting the absorbed power-law model in the energy range of 0.3–10 keV, given in the SWIFT X-ray telescope point-source catalog (1SXPS, Evans *et al.* 2014).

2.2 *Optical data*

In order to characterize the optical properties of quasar, we explored the spectral information provided in Zamfir *et al.* (2010), Sulentic *et al.* (2007), Marziani *et al.* (2003) and Grupe *et al.* (2004). We used 4DE1 parameter space measures of FWHM Hβ_{BC} (broad line) and the optical FeII blue blend (RFeII = W(FeII 4570)/W(Hβ_{BC})). These are the parameters that describe the optical plane of 4DE1. The sample of Zamfir *et al.* consists of 470 radio loud, low-redshift quasars with the highest S/N spectra extracted from SDSS DR5. The Marziani *et al.* sample includes 215 type 1 AGNs/radio galaxy nuclei and low-z quasars. The data from Sulentic *et al.* (2007) involves 130 sources from the HST archive for which reliable CIV λ1549 Å properties could be measured. The sample of objects taken from the database of Grupe includes 110 sources including narrow-line Seyfert 1 galaxies (half of the sample) and broad-line Seyfert 1's. Excluding the common sources the final sample consists of 690 Type 1 quasars. We matched it with the XMM-Newton and SWIFT X-ray databases and allowed a maximum difference between optical and X-ray positions of 6 and 5.5 arcsec for XMM-Newton and SWIFT data, respectively. We obtained 160 and 214 matches for XMM-Newton and Swift, respectively.

In order to enlarge the sample we matched the XMM-Newton spectral-fit database with the Sloan Digital Sky Survey Quasar Catalog (DR7 & DR10) and obtained 672 matches. This yielded 109 new SDSS spectra with high enough S/N (>15) to enable reliable measurements for Hβ_{BC} and FeII λ4570 and with XMM-Newton spectral information. In order to separate these sources into the population bins, we estimated FWHM(Hβ_{BC}) and FeII ratio from SDSS spectra using SPLOT and NGAUSSFIT routines from the IRAF package. Our final optically selected sample consists of 813 different sources of which 262 have spectral information from XMMFITCAT. This represents our sample for soft X-ray excess analysis. In Table 1, we present the total number of sources in the three spectral ranges: full, soft and hard. They correspond to the sources for which good spectral fitting was obtained in the Corral *et al.* (2015) catalog and with sufficiently accurate measurements of the optical parameters enable location in the 4DE1 optical plane for the three X-ray spectral ranges. We also include in Table 1 sources that have information about the full spectral range in Swift.

Table 1. Number of sources detected in X-rays.

Parameter	Matches	Energy range (keV)
XMM-N		
$\Gamma_{\rm full}$	259	0.5–10.0
$\Gamma_{\rm soft}$	261	0.5–2.0
$\Gamma_{\rm hard}$	219	2.0–10.0
SWIFT		
$\Gamma_{\rm full}$	214	0.3–10.0

3. Analysis and results

3.1 *Population A and B*

Following the classification of Sulentic *et al.* (2000a, b), we divided our sample into populations A and B based on FWHM Hβ_{BC}: Pop. A (FWHM Hβ_{BC} <4000 km/s) and Pop. B (FWHM Hβ_{BC} >4000 km/s). Figure 1 shows the location in the 4DE1 optical plane of all quasars in our sample, where the blue horizontal line marks the boundary (4000 km/s) between the two populations.

3.2 *Statistical analysis*

We compare X-ray spectral characteristics of the two quasar populations A and B. Table 2 gives statistical information (median value, quartile 1 and quartile 3) derived for $\Gamma_{\rm full}$, $\Gamma_{\rm soft}$ and $\Gamma_{\rm hard}$ given by the XMM-Newton database. All parameters were derived for population A and B separately. In order to check for observational bias and to ensure that our results are not affected by the quality of the data, we checked the distribution of the number of counts for populations A and B, in the soft, hard and full bands. There are no signicant differences between the distibutions of number of counts of both populations so we do not expect any influence in our results.

Two statistical tests were performed, the Kolmogorov–Smirnov and a Student *t*-test, to estimate the statistical significance of the difference of the spectral indices between populations A and B. We find a statistically significant difference. The probability that the two populations come from the same parent population is very small

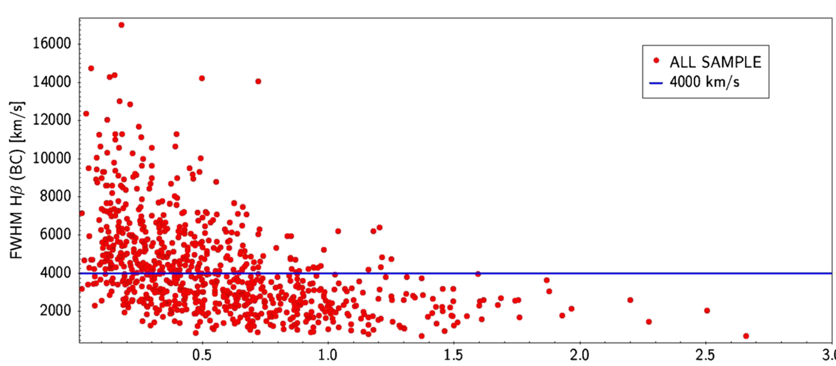

Figure 1. Our sample in the optical plane of the 4DE1 parameter space.

Table 2. XMM-Newton X-ray spectral parameters for full sample.

Parameter	Quartile 1	Median	Quartile 3	No. of sources
Pop. A				
Γ_{full}	1.952	2.183	2.474	133
Γ_{soft}	2.121	2.384	2.730	133
Γ_{hard}	1.712	2.001	2.176	107
Pop. B				
Γ_{full}	1.642	1.903	2.050	126
Γ_{soft}	1.876	2.041	2.213	128
Γ_{hard}	1.522	1.744	1.921	112

in all cases (less to 7.3×10^{-8}) as measured by a Kolmogorov–Smirnov test. We also use the Student *t*-test to determine if the means of the two populations are significantly different and taking into account different variances of both populations. The results are confirmed by the parametric Student's *t*-test which gives values for the *t* statistics of 7.8, 4.5 and 6.8 for XMM-Newton Γ_{soft}, Γ_{hard} and Γ_{full} respectively. In all cases the probabilities are smaller than 1×10^{-5}. We note that gamma soft is a better discriminatior between the populations while gamma hard is more similar. Γ_{full} lies in between but it discriminates at a probability level of 9.0×10^{-11} as measured by *t*.

Figure 2 shows the histogram normalized by the variance of the distributions of values for XMM-Newton Γ_{soft} (261 sources) for both populations A and B.

We found that Γ_{full} provided by 1SXPS may also be a discriminator between the two populations. Figure 3 presents a comparison of the Γ_{full} measures derived from SWIFT spectra for populations A and B.

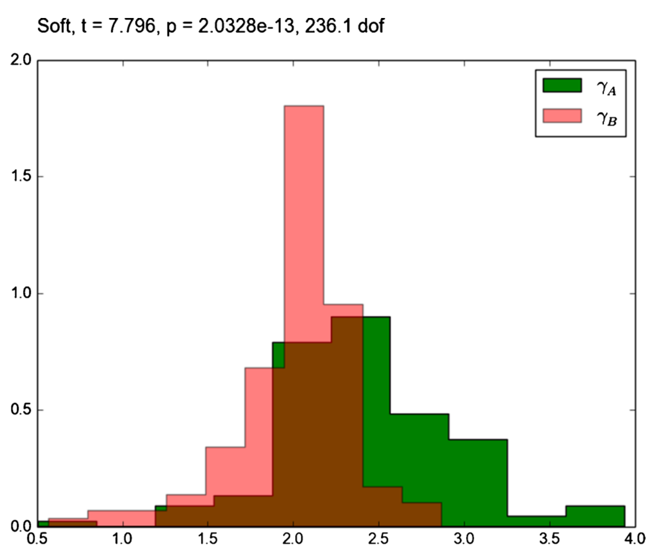

Figure 2. The distributions of the XMM-Newton Γ_{soft} values for populations A and B.

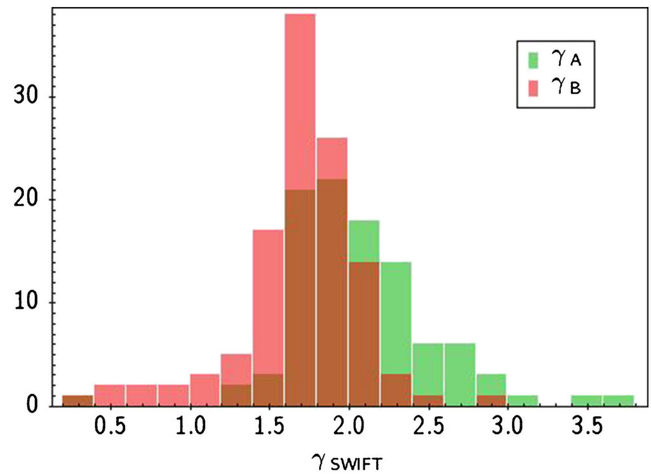

Figure 3. The distributions of the SWIFT Γ_{full} values for populations A and B.

3.3 *SWIFT and XMM-Newton*

We expected to find the best Pop. A and Pop. B separation in Γ_{soft} measures. Γ_{soft} is not available from SWIFT so we compared XMM-Newton Γ_{soft} and SWIFT Γ_{full} measures for the sources in common (∼80). Figure 4 shows values of Γ_{soft} from XMM-Newton versus Γ_{full} from SWIFT. There is a good relation between the values from both instruments. Therefore we use the values of Γ_{full} from SWIFT as

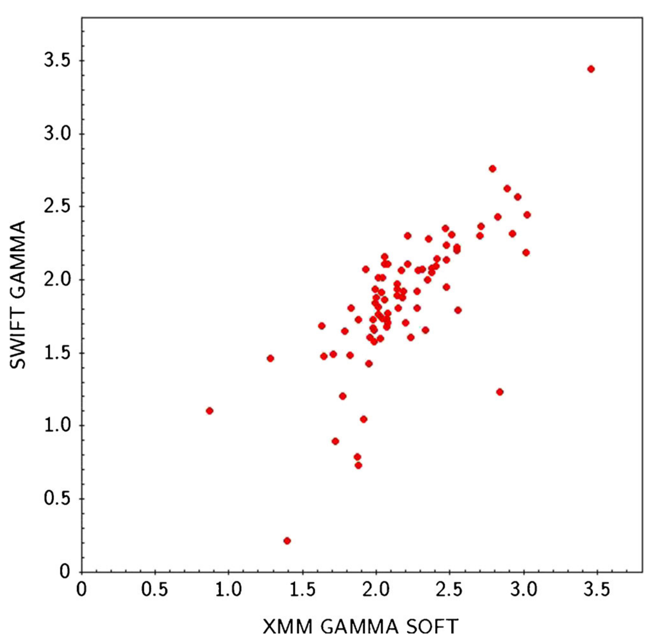

Figure 4. The comparison of values of Γ_{soft} from XMM-Newton versus values of Γ_{full} from SWIFT for the sources in common.

Table 3. SWIFT X-ray spectral parameters for full sample.

Parameter	Median	Quartile 1	Quartile 3	Sources
Pop. A $\Gamma_{\rm full}$	2.00	1.77	2.30	99
Pop. B $\Gamma_{\rm full}$	1.73	1.58	1.89	115

a confirmation of our XMM-Newton results. Table 3 presents values of $\Gamma_{\rm full}$ from SWIFT.

4. Conclusions

X-ray spectral differences between the two populations of quasars classified using optical and UV spectral measures are presented. We find significant differences between populations A and B spectral properties. While not included in the original PCA studies, it is clear that $\Gamma_{\rm soft}$ is a valuable additional diagnostic for separating high and low accreting AGN. Both XMM-Newton and Swift measures show the Pop. A–B difference. While there is some overlap (80 sources), SWIFT measures involve 130 AGN not observed by XMM. Lower luminosity Type 1 AGN dominate both samples making it unclear if the X-ray dichotomy extends to high z quasars, often 2–3 dex higher $L_{\rm bol}$ than the majority of sources in these samples. $\Gamma_{\rm soft}$ correlates strongly with both CIV λ1549 Å blueshift and optical FeII strength (RFeII) measures. Those measures become stronger in higher L sources leading us to expect a stronger X-ray signature at high z.

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