Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **480**, 1819–1830 (2018)
Advance Access publication 2018 July 18

doi:10.1093/mnras/sty1879

BAT AGN Spectroscopic Survey – XII. The relation between coronal properties of active galactic nuclei and the Eddington ratio

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Accepted 2018 July 5. Received 2018 July 5; in original form 2018 February 16

ABSTRACT

The bulk of the X-ray emission in active galactic nuclei (AGNs) is produced very close to the accreting supermassive black hole (SMBH), in a corona of hot electrons which up scatters optical and ultraviolet photons from the accretion flow. The cut-off energy ($E_{\rm C}$) of the primary X-ray continuum emission carries important information on the physical characteristics of the X-ray emitting plasma, but little is currently known about its potential relation with the properties of accreting SMBHs. Using the largest broad-band (0.3–150 keV) X-ray spectroscopic study available to date, we investigate how the corona is related to the AGN luminosity, black hole mass and Eddington ratio ($\lambda_{\rm Edd}$). Assuming a slab corona the median values of the temperature and optical depth of the Comptonizing plasma are $kT_{\rm e} = 105 \pm 18$ keV and $\tau = 0.25 \pm 0.06$, respectively. When we properly account for the large number of $E_{\rm C}$ lower limits, we find a statistically significant dependence of the cut-off energy on the Eddington ratio. In particular, objects with $\lambda_{\rm Edd} > 0.1$ have a significantly lower median cut-off energy ($E_{\rm C} = 160 \pm 41$ keV) than those with $\lambda_{\rm Edd} \leq 0.1$ ($E_{\rm C} = 370 \pm 51$ keV). This is consistent with the idea that radiatively compact coronae are also cooler, because they tend to avoid the region in the temperature-compactness parameter space where runaway pair production would dominate. We show that this behaviour could also straightforwardly explain the suggested positive correlation between the photon index (Γ) and the Eddington ratio, being able to reproduce the observed slope of the Γ–$\lambda_{\rm Edd}$ trend.

Key words: galaxies: active – galaxies: Seyfert – quasars: general – quasars: supermassive black holes – X-rays: general.

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1 INTRODUCTION

Accreting supermassive black holes (SMBHs) are known to ubiquitously produce radiation in the X-ray band. The X-ray emission of these active galactic nuclei (AGNs) is thought to be produced in a *corona* of hot electrons, which up-scatters optical and UV photons into the X-ray band through inverse Compton scattering (e.g. Haardt & Maraschi 1991, 1993; Liu et al. 2015, 2017). The size of the X-ray corona has been shown to be relatively small ($5-10\,R_{\rm g}$, where $R_{\rm g}=GM_{\rm BH}/c^2$ is the gravitational radius for a SMBH of mass $M_{\rm BH}$) from the rapid X-ray variability (e.g. McHardy et al. 2005), and the short time-scales of X-ray eclipses (e.g. Risaliti et al. 2005, 2011). This has been also confirmed by microlensing studies (e.g. Chartas et al. 2009), which have found a half-light radius of the corona of $\sim 6\,R_{\rm g}$. Reverberation studies of X-ray radiation reprocessed by the accretion disc have suggested that the X-ray source is located very close to the SMBH and the accretion disc (e.g. Fabian et al. 2009; Zoghbi et al. 2012; De Marco et al. 2013; Kara et al. 2013; Reis & Miller 2013), typically within $3-10\,R_{\rm g}$. Despite these advances in localization and size estimates of the X-ray source, its physical characteristics are still debated. Besides providing critical insights on the physics of the innermost regions of SMBHs, a clear understanding of the typical characteristics of the X-ray emitting plasma for different intervals of the accretion rate is extremely important to assess the impact of radiative heating (Xie, Yuan & Ho 2017) in the feedback process linking AGNs to their host galaxies (e.g. Ferrarese & Merritt 2000; Gebhardt et al. 2000; Schawinski et al. 2006; Fabian 2012; Kormendy & Ho 2013; King & Pounds 2015).

X-ray spectroscopy, and in particular the study of the primary X-ray emission produced in the Comptonizing plasma, can provide important insights on the physical parameters of the corona, such as its temperature ($kT_{\rm e}$) and optical depth (τ). The two main spectral parameters carrying information on the physical properties of the X-ray corona are the photon index (Γ) and the energy of the cut-off ($E_{\rm C}$; e.g. Mushotzky, Done & Pounds 1993). While the photon index has been routinely studied over the past two decades by observations carried out in the 0.3–10 keV band, the cut-off energy has been more difficult to constrain, since it requires good-quality data above 10 keV. Indirect constraints on the cut-off energy have been obtained by Gilli, Comastri & Hasinger (2007), who, studying the cosmic X-ray background (CXB, see also Treister, Urry & Virani 2009), showed that the mean cut-off energy should lie below 300 keV; Treister & Urry (2005) and Ueda et al. (2014) were able to reproduce the CXB assuming $E_{\rm C}=300$ keV; fitting the X-ray luminosity function of local AGNs in four energy bands, Ballantyne (2014) found that the typical cut-off energy should be $E_{\rm C}\sim 200$–450 keV. Spectroscopic studies carried out using the Gamma Ray Observatory/OSSE (e.g. Zdziarski, Johnson & Magdziarz 1996; Johnson et al. 1997), BeppoSAX (e.g. Nicastro et al. 2000; Dadina 2007), *INTEGRAL* IBIS/ISGRI (e.g. Beckmann et al. 2009; Molina et al. 2009; Lubiński et al. 2010, 2016; Panessa et al. 2011; Ricci et al. 2011; de Rosa et al. 2012; Malizia et al. 2014), *Swift*/BAT (e.g. Vasudevan et al. 2013) and *Suzaku*/PIN (e.g. Tazaki et al. 2011) were able to constrain the cut-off energies of several local bright AGNs.

More recently, in Ricci et al. (2017a), we carried out the largest study of broad-band X-ray spectra (0.3–150 keV) to date (836 AGNs), showing that, in the large majority ($\simeq$80 per cent) of the non-blazar AGNs, the spectral slope of the 14–195 keV emission is steeper than that in the 0.3–10 keV band. This suggests that a high-energy cut-off is almost ubiquitous in AGNs. The detailed broad-band X-ray spectral analysis of all sources of the sample showed that the median value of the cut-off energy of local AGN is 200 ± 29 keV (Ricci et al. 2017a). The recent launch of *NuSTAR* (Harrison et al. 2013) has greatly improved our understanding of cut-off energies, allowing to accurately constrain this parameter for a growing number of AGNs, most of which reside at low redshifts (e.g. Ballantyne et al. 2014; Brenneman et al. 2014; Matt et al. 2014; Marinucci et al. 2014; Parker et al. 2014; Baloković et al. 2015; Lohfink et al. 2015, 2017; Matt et al. 2015; Ursini et al. 2015; Lanzuisi et al. 2016; Kara et al. 2017; Tortosa et al. 2017, 2018b,a; Xu et al. 2017). Exploiting the revolutionary capabilities of *NuSTAR*, Fabian et al. (2015; see also Fabian et al. 2017) have shown that coronae lie close to the boundary of the region in the temperature–compactness parameter space which is forbidden due to runaway pair production (see Section 4). Studying 19 *Swift*/BAT AGNs with *NuSTAR*, Tortosa et al. (2018a) found no evidence of a significant correlation between $E_{\rm C}$ and black hole mass or Eddington ratio. However, the sample of bright AGNs that are observed by *NuSTAR* and have reliable determinations of these key SMBH properties is still small, and does not allow to exclude the existence of relations between the coronal properties and the physical characteristics of the SMBH.

In order to improve our understanding of the properties of accreting SMBHs in the local Universe, our group has been systematically studying the properties of *Swift*/BAT AGNs across the electromagnetic spectrum, in the framework of the BAT AGN Spectroscopic Survey (BASS;[1] Koss et al. 2017; Ricci et al. 2017a). Previous publications based on BASS have studied the optical lines (Berney et al. 2015; Oh et al. 2017), the near-infrared emission (Lamperti et al. 2017), the X-ray photon index (Trakhtenbrot et al. 2017) and the absorption properties (Ricci et al. 2015, 2017b; Shimizu et al. 2018) of *Swift*/BAT AGNs. Exploiting the rich multiwavelength database available for BASS AGNs, here we investigate the relation between the high-energy cut-off and the fundamental properties of AGNs, such as their luminosity (L), black hole mass ($M_{\rm BH}$), and Eddington ratio ($\lambda_{\rm Edd}=L/L_{\rm Edd}$, see equation 1). The paper is structured as follows. In Section 2, we introduce the sample used for this work, while in Section 3 we study how the cut-off energy is related to luminosity, black hole mass, and Eddington ratio, showing that AGNs accreting at high Eddington ratios ($\log\lambda_{\rm Edd}\geq -1$) typically have lower cut-off energies than those accreting at lower Eddington ratios ($\log\lambda_{\rm Edd}< -1$). In Section 4, we discuss how our sources are distributed in the temperature–compactness parameter space, and how this relates to the dissimilar typical cut-off energies of AGN populations accreting at different $\lambda_{\rm Edd}$. In Section 5, we investigate the relation between the optical depth of the Comptonizing plasma and the properties of the accreting SMBH. In Section 6, we show how the fact that AGNs avoid the region in the temperature–compactness parameter space where runaway pair production takes place would produce the observed correlation between the photon index and the Eddington ratio. Finally, in Section 7 we present our conclusions and summarize our findings.

2 BASS: SAMPLE AND DATA

The Burst Alert Telescope (BAT; Barthelmy et al. 2005) on board the *Neil Gehrels Swift Observatory* (Gehrels et al. 2004) has been scanning the whole sky in the 14-195 keV band since its launch in 2005, detecting 838 AGNs in the first 70-months of operations (Baumgartner et al. 2013; Ricci et al. 2017a). The multiwavelength survey BASS has collected data in the radio, infrared, optical, and X-rays for the large majority of these objects. In the following, we

[1] http://www.bass-survey.com

report on the X-ray (Section 2.1) and optical (Section 2.2) data used for this work.

2.1 X-ray data

The cut-off energies and the AGN luminosities used here are taken from the BASS X-ray catalogue (Ricci et al. 2017a), which reports the broad-band X-ray spectral properties for the 836 AGNs detected by *Swift*/BAT in its first 70 months of operations (≃99.8 per cent of the total sample) for which soft X-ray (0.3–10 keV) spectra were available. This was done by combining the 70-month averaged *Swift*/BAT spectra with shorter pointed observations carried out by *Swift*/XRT, *XMM-Newton*/EPIC, *Chandra*/ACIS, *Suzaku*/XIS, and *ASCA* GIS/SIS. The spectral analysis was carried out over the entire 0.3–150 keV range, using a total of 26 different spectral models, which include various emission components. The broad-band X-ray coverage allowed to recover several important properties of these AGNs, such as their intrinsic X-ray luminosity, column densities, photon indices, and cut-off energies. For further details on the spectral analysis, we refer the reader to Ricci et al. (2017a). We focus here only on the 317 unobscured [i.e. $\log(N_{\rm H}/{\rm cm}^{-2}) < 22$] AGNs for which $E_{\rm C}$ could be constrained[2] (228 lower limits and 89 values, see Fig. 1), to avoid possible degeneracies due to the additional spectral curvature introduced by heavy obscuration above 10 keV.

2.2 Optical data, black hole masses, and Eddington ratio

The analysis of the optical spectra of 642 *Swift*/BAT accreting SMBHs is reported in Koss et al. (2017), and allowed us to obtain black hole masses for 429 non-blazar AGNs. Of these, 232 are unobscured, while 197 are obscured. The black hole masses were obtained through several fundamentally different approaches: (i) 'direct' methods (i.e. maser emission, spatially resolved gas- or stellar-kinematics, reverberation mapping); (ii) single-epoch spectra of broad Hβ and Hα emission lines (e.g. Trakhtenbrot & Netzer 2012; Greene & Ho 2005, respectively); (iii) stellar velocity dispersions (σ_*) and the $M_{\rm BH}$–σ_* relation (Kormendy & Ho 2013). Of the 232 unobscured AGNs with black hole mass estimates, our broad-band X-ray spectral analysis could constrain cut-off energies for a total of 211 sources, of which 144 are lower limits and 67 are values. For these objects, $M_{\rm BH}$ was obtained using broad Hβ (144), reverberation mapping (31), broad Hα (18), velocity dispersion (16), stellar (1), and gas (1) kinematics. These 211 AGNs are a representative subset of sources of the BAT sample of unobscured AGNs, having a very similar luminosity distribution. In the following, we will use this as our final sample.

The Eddington luminosity was calculated using the following relation:

$$L_{\rm Edd} = \frac{4\pi G M_{\rm BH} m_{\rm p} c}{\sigma_{\rm T}}, \qquad (1)$$

where G is the gravitational constant, $m_{\rm p}$ is the mass of the proton, c is the speed of light, and $\sigma_{\rm T}$ is the Thomson cross-section. The bolometric luminosity ($L_{\rm Bol}$) of the AGN in our sample was calculated from the intrinsic 2–10 keV luminosity, using a 2–10 keV bolometric correction of $\kappa_{2-10} = 20$ (Vasudevan & Fabian 2009; $L_{\rm Bol} = \kappa_{2-10} \times L_{2-10}$). In Section 3, we discuss the effects of considering a dependence of κ_{2-10} on $L_{\rm Bol}$ and/or $\lambda_{\rm Edd}$ (e.g. Vasudevan & Fabian 2009). The typical uncertainty on $\lambda_{\rm Edd}$ is conservatively estimated to be ∼0.5 dex (see Koss et al. 2017).

[2]For the remaining unobscured AGNs, the cut-off energy could not be constrained by the fit.

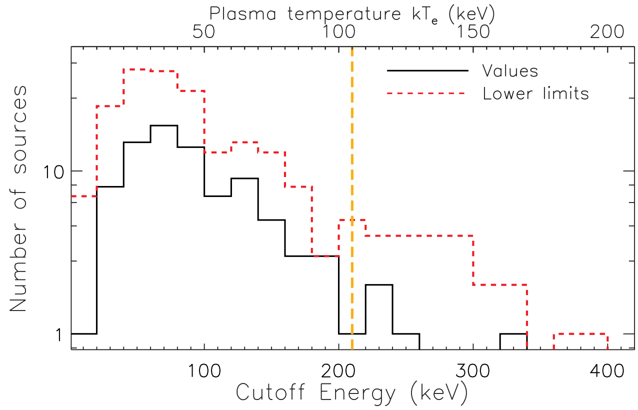

Figure 1. Histogram of the cut-off energy of unobscured ($N_{\rm H} < 10^{22}{\rm cm}^{-2}$) sources from the *Swift*/BAT AGN catalogue of Ricci et al. (2017a). The temperature of the Comptonizing plasma was calculated assuming $kT_{\rm e} = E_{\rm C}/2$ (see Section 4). The continuous black and dashed red lines illustrate the values and the lower limits, respectively. The vertical dashed orange line shows the median cut-off energy and plasma temperature of the sample ($E_{\rm C} = 210 \pm 36$ keV, i.e. $kT_{\rm e} = 105 \pm 18$ keV), calculated taking into account the lower limits.

3 THE RELATION BETWEEN THE CUT-OFF ENERGY AND THE PHYSICAL PROPERTIES OF THE ACCRETING SMBH

Using the BASS database, we explored the relation between the cut-off energy and the properties of the accreting SMBH, such as its luminosity, black hole mass, and Eddington ratio. In the left-hand panel of Fig. 2, we show the cut-off energy versus the 14–150 keV intrinsic (absorption and *K*-corrected) luminosity (L_{14-150}). Since the sample contains a large number of lower limits, we used the Kaplan–Meier estimator within the ASURV package (Feigelson & Nelson 1985; Isobe, Feigelson & Nelson 1986), using a PYTHON implementation (see section 5 of Shimizu et al. 2016 for details) to calculate the median values of $E_{\rm C}$ in several luminosity bins. As shown in the right-hand panel of Fig. 2, the sample does not show significant changes of the cut-off energy with the AGN luminosity. We performed a linear fit on the binned data, which include the censored values, using a relation of the form $E_{\rm C} = \alpha + \beta \log L_{14-150}$. The p-value of the correlation is 0.74, suggesting that no significant trend exists between the cut-off energy and the intrinsic 14–150 keV AGN luminosity.

In the left-hand panel of Fig. 3, we plot the cut-off energy versus $M_{\rm BH}$ for the 211 unobscured AGNs for which this parameter is available. The rebinned plot (right-hand panel of Fig. 3), shows a positive trend. The median $E_{\rm C}$ appears to increase with $M_{\rm BH}$, from 123 ± 50 keV for $5 \leq \log(M_{\rm BH}/{\rm M}_\odot) < 6$ to 323 ± 51 keV for $9 \leq \log(M_{\rm BH}/{\rm M}_\odot) < 10$. Fitting the data with $E_{\rm C} = \gamma + \delta \log M_{\rm BH}$, we found a significant correlation, with a p-value of 0.003 and a slope of $\delta = 49 \pm 16$. A similar trend is observed when considering only the objects for which the black hole mass was estimated using broad Hβ (blue line in Fig. 3).

The left-hand panel of Fig. 4 shows the scatter plot of $E_{\rm C}$ versus Eddington ratio. The rebinned plot (right-hand panel of Fig. 4) shows a negative trend, with a clear difference in the typical $E_{\rm C}$ for objects accreting at high and low Eddington ratio: the me-

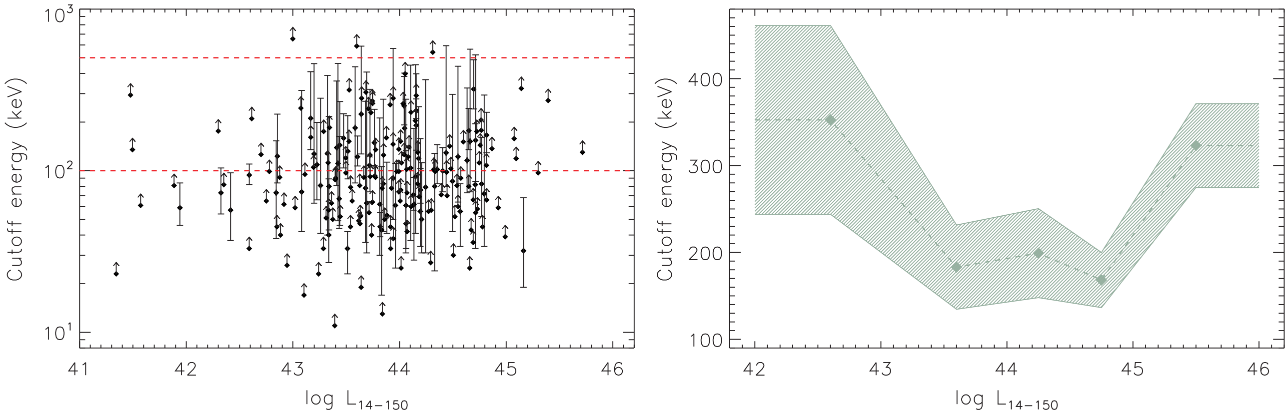

Figure 2. Left-hand panel: Cut-off energy versus the 14–150 keV intrinsic luminosity (in erg s^{-1}) for the sources in our sample. The red dashed lines show the interval of cut-off energies shown in the right-hand panel. Right-hand panel: Median values of the cut-off energy for different bins of L_{14-150}, calculated including the lower limits using the Kaplan–Meier estimator within the ASURV package. The shaded area corresponds to the median absolute deviation.

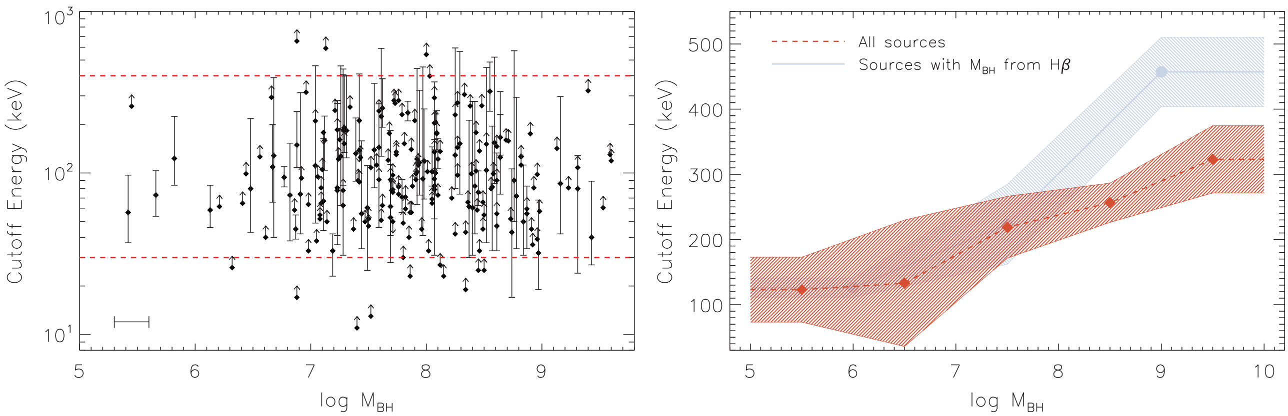

Figure 3. Left-hand panel: Cut-off energy versus M_{BH} (in $M_{\odot}$) for the sources in our sample. The red dashed lines show the interval of cut-off energies shown in the right-hand panel. The bar in the bottom left corner shows the typical uncertainty of M_{BH}. Right-hand panel: Median values of the cut-off energy for different intervals of M_{BH} for the whole sample (red dashed line) and for the objects for which M_{BH} was estimated using Hβ (blue dot-dot dashed line). The medians were calculated including the lower limits using the Kaplan–Meier estimator within the ASURV package. The shaded area represents to the median absolute deviation.

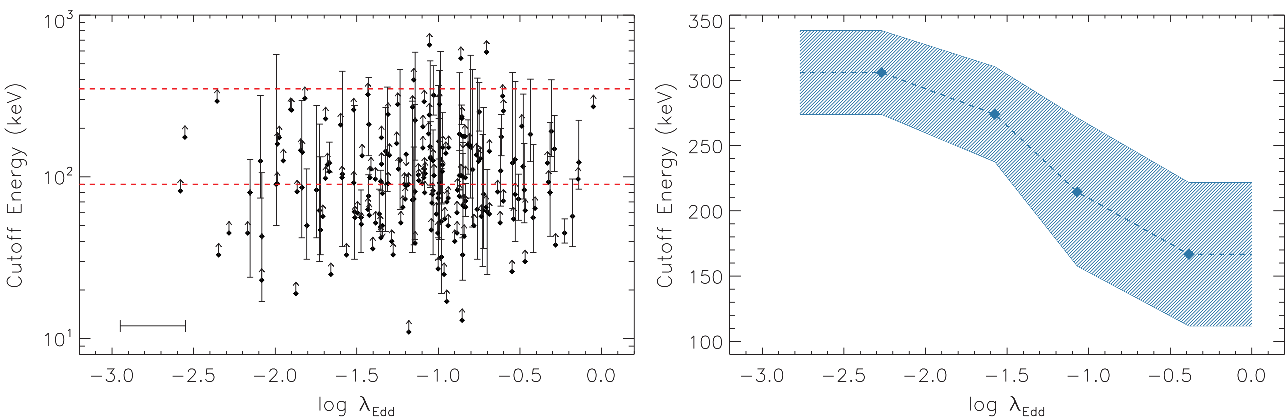

Figure 4. Left-hand panel: Cut-off energy versus the Eddington ratio for the sources in our sample. The red dashed lines show the interval of cut-off energies shown in the right-hand panel. The bar in the bottom left corner shows the typical uncertainty of λ_{Edd}. Right-hand panel: Median values of the cut-off energy for different intervals of λ_{Edd}. The shaded area corresponds to the median absolute deviation.

dian cut-off energy of the AGN accreting at $\lambda_{Edd} \leq 0.1$ is $E_C = 370 \pm 51$ keV, while the sources at $0.1 < \lambda_{Edd} \leq 1$ have a median of $E_C = 160 \pm 41$ keV, which implies a 3.2σ difference between the two subsets of sources. Such a difference is confirmed also considering only the closest AGNs ($z \leq 0.05$): for $\lambda_{Edd} \leq 0.1$ we find $E_C = 506 \pm 82$ keV, while for $0.1 < \lambda_{Edd} \leq 1$ the median cut-off energy

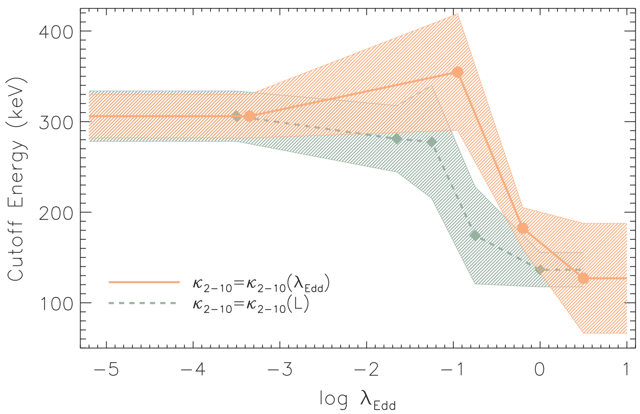

Figure 5. Median values of the cut-off energy for different intervals of Eddington ratio considering different 2–10 keV bolometric corrections: the $\lambda_{\rm Edd}$-dependent bolometric corrections of Vasudevan & Fabian (2007) (orange dot–dot–dashed line) and the luminosity-dependent bolometric corrections of Lusso et al. (2012) (green dashed line). The shaded area corresponds to the median absolute deviation.

is $E_{\rm C} = 164 \pm 46$ keV (i.e. the difference between the subsamples is 3.6σ). Ignoring the lower limit on $E_{\rm C}$ results in a rather flat trend, and no significant difference in $E_{\rm C}$ is found between objects accreting at low and high $\lambda_{\rm Edd}$. Fitting the rebinned data with $E_{\rm C} = \epsilon + \zeta \log \lambda_{\rm Edd}$, we obtained a p-value of 0.01, and a slope of $\zeta = -74 \pm 31$.

In Fig. 5, we illustrate the effect of adopting $\lambda_{\rm Edd}$-dependent (Vasudevan & Fabian 2007, orange dot–dot–dashed line) and luminosity-dependent (Lusso et al. 2012, green dashed line) 2–10 keV bolometric corrections to the relation between $E_{\rm C}$ and $\lambda_{\rm Edd}$. In both cases, we find the same trend observed adopting a constant $\kappa_{2-10} = 20$: objects accreting at higher Eddington ratios tend to have lower cut-off energies. In particular we find that, using the corrections of Vasudevan & Fabian (2007), the median cut-off energy drops from $E_{\rm C} = 342 \pm 27$ keV for $\log \lambda_{\rm Edd} \leq -0.7$ to $E_{\rm C} = 163 \pm 45$ keV for $\log \lambda_{\rm Edd} > -0.7$, implying a difference significant at the 3.4σ level. Considering the corrections of Lusso et al. (2012) the difference is of 2.8σ ($E_{\rm C} = 359 \pm 54$ keV for $\log \lambda_{\rm Edd} \leq -1$ and $E_{\rm C} = 160 \pm 45$ keV for $\log \lambda_{\rm Edd} > -1$).

To further test the relation between $E_{\rm C}$, $M_{\rm BH}$, and $\lambda_{\rm Edd}$, we used a different approach to calculate the median values of the cut-off energy for different values of black hole mass and Eddington ratio. This was done performing 1000 Monte Carlo simulations for each object of our sample, substituting the cut-off energies we could constrain with values that were randomly selected from a Gaussian distribution centered on $E_{\rm C}$, and with a standard deviation given by the uncertainty. Lower limits (LL) were substituted with values randomly selected from a uniform distribution in the interval [LL, $E_{\rm C}^{\rm max}$], where $E_{\rm C}^{\rm max} = 1000$keV is the maximum cut-off energy. For each Monte Carlo run, we calculated the median in two different bins of $M_{\rm BH}$ and $\lambda_{\rm Edd}$, and finally we calculated the means of all simulations. For $10^5 \leq M_{\rm BH}/M_{\odot} < 10^{7.5}$, we obtain $E_{\rm C} = 312 \pm 44$ keV, while for $10^{7.5} \leq M_{\rm BH}/M_{\odot} < 10^{10}$ we found $E_{\rm C} = 416 \pm 30$ keV. This implies $a \simeq 2\sigma$ difference between the two subsamples. For $\lambda_{\rm Edd} \leq 0.1$, we find $E_{\rm C} = 432 \pm 30$ keV, while for $0.1 < \lambda_{\rm Edd} \leq 1$ the median cut-off energy is $E_{\rm C} = 307 \pm 37$ keV. This implies a difference significant at the 2.6σ level. It should be remarked that the median values obtained using this approach are typically larger than those we found using the survival analysis. This is due to the fact that we are assuming a flat distribution for the lower limits, which likely does not represent the real physical distribution of plasma temperatures, and largely increases the number of objects with $E_{\rm C} > 500$ keV.

To investigate whether the Eddington ratio or the black hole mass is the main physical parameter responsible for differences in the cut-off energy, in Figs 6–8 we plot the median values of $E_{\rm C}$ as a function of luminosity, black hole mass and Eddington ratio. In each of the six panels, we illustrate the dependence on one of these parameters for two subsets of sources covering different intervals of the other parameters. No clear dependence of $E_{\rm C}$ on the X-ray luminosity is found dividing the sample into bins of $M_{\rm BH}$ and $\lambda_{\rm Edd}$ (left-hand and right-hand panels of Fig. 6, respectively), although a difference can be observed between the low and high Eddington ratio subsamples. Interestingly, while a possible trend between $E_{\rm C}$ and $M_{\rm BH}$ is observed dividing the sample in two luminosity intervals (left-hand panel of Fig. 7), such a relation disappears when splitting the sources into bins of Eddington ratio (right-hand panel of Fig. 7). A similar trend is observed considering only objects for which $M_{\rm BH}$ was obtained from Hβ. This, together with the fact that the subsample with $\lambda_{\rm Edd} \leq 0.1$ has a lower median $E_{\rm C}$ than that with $0.1 < \lambda_{\rm Edd} \leq 1$ across the interval of black hole masses spanned by the data suggests that the correlation between $E_{\rm C}$ and $\lambda_{\rm Edd}$ is the main relation. This is confirmed by the fact that, regardless of the luminosity (left-hand panel of Fig. 8) and black hole mass (right-hand panel of Fig. 8), sources with high $\lambda_{\rm Edd}$ tend to have lower cut-off energies than those with low mass-normalized accretion rates.

4 AGNS IN THE TEMPERATURE–COMPACTNESS PARAMETER SPACE

Two important parameters of AGN coronae are their compactness (Cavaliere & Morrison 1980; Guilbert, Fabian & Rees 1983) and normalized temperature. The compactness parameter (l) is defined as

$$l = \frac{L_{\rm X}}{R_{\rm X}} \frac{\sigma_{\rm T}}{m_{\rm e} c^3} = 4\pi \frac{\lambda_{\rm Edd}}{\kappa_{\rm x}} \frac{m_{\rm p}}{m_{\rm e}} \frac{R_{\rm g}}{R_{\rm X}}, \quad (2)$$

where $L_{\rm X}$ is the X-ray luminosity of the source, $R_{\rm X}$ is the radius of the X-ray source, $\kappa_{\rm x}$ is the X-ray bolometric correction, $m_{\rm e}$ is the mass of the electron, $m_{\rm p}$ is the mass of the proton, and $\sigma_{\rm T}$ is the Thomson cross-section. The compactness was calculated using the 0.1–200 keV luminosity, which was obtained from the intrinsic 14–150 keV luminosity, assuming $\Gamma = 1.8$ (Mushotzky 1982; Winter et al. 2009; Ricci et al. 2017a), while the 0.1–200 keV bolometric correction was set to $\kappa_{\rm x} = 3.87$, which corresponds to our assumption of $\kappa_{2-10} = 20$ (Vasudevan & Fabian 2009) and the same Γ. The normalised temperature parameter (Θ) is:

$$\Theta = \frac{kT_{\rm e}}{m_{\rm e} c^2} = \frac{E_{\rm C}}{2 m_{\rm e} c^2}. \quad (3)$$

In the above equation, we considered that $kT_{\rm e} = E_{\rm C}/2$, which is an approximation valid for optically thin plasma[3] for a corona with slab geometry (Petrucci et al. 2000, 2001), obtained using the Comptonization model of Haardt, Maraschi & Ghisellini (1994). Considering this relation, the median temperature of the X-ray emitting plasma for the objects of our sample is $kT_{\rm e} = 105 \pm 18$ keV.

In the left-hand panel of Fig. 9, we show the temperature–compactness diagram for the *Swift*/BAT AGNs in our sample for

[3] As discussed in Petrucci et al. (2001), for $\tau \gg 1$ then $kT_{\rm e} \simeq E_{\rm C}/3$.

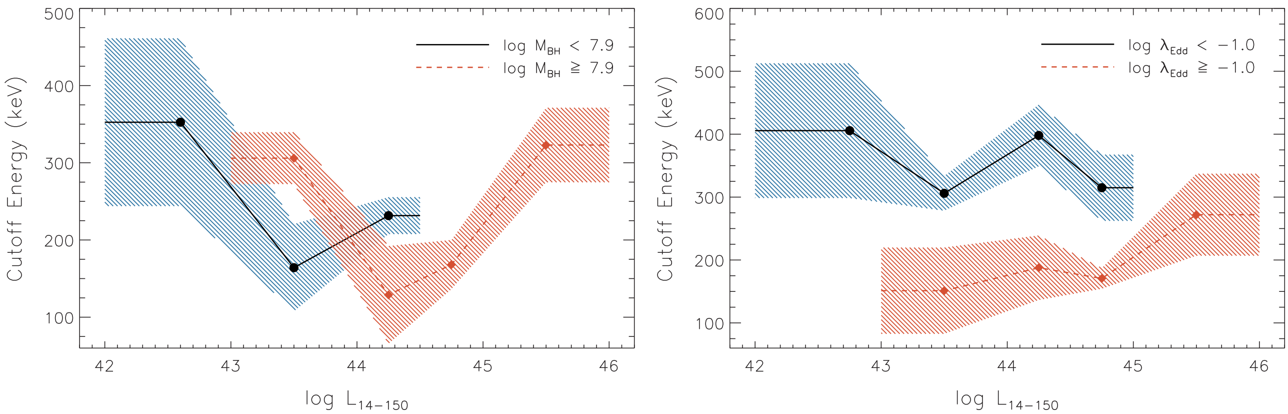

Figure 6. Cut-off energy versus the luminosity for two ranges of black hole mass (left-hand panel, in units of $M_{\odot}$) and of Eddington ratio (right-hand panel). Both panels show the median values of the cut-off energy for different intervals of L_{14-150} (in erg s^{-1}). The shaded areas corresponds to the median absolute deviations. The figures show little or no dependence of E_C on the luminosity, while there is a clear difference between sources accreting at different Eddington ratios: the AGN with $\lambda_{Edd} \geq 0.1$ tend to have lower cut-off energies than those with $\lambda_{Edd} < 0.1$, even at similar luminosities.

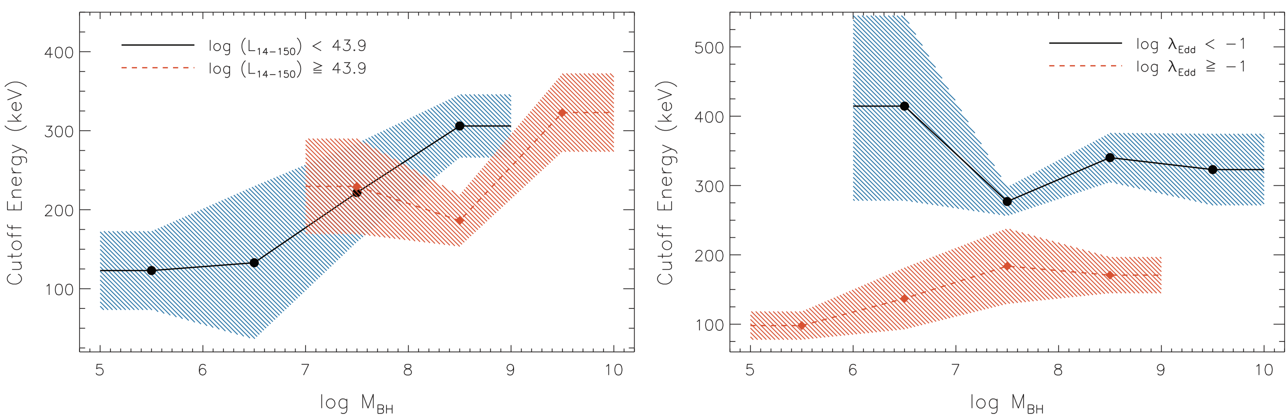

Figure 7. Cut-off energy versus the M_{BH} (in $M_{\odot}$) for two intervals of luminosity (left-hand panel, in erg s^{-1}) and Eddington ratio (right-hand panel). Both panels show the median cut-off energies; the shaded areas corresponds to the median absolute deviations. The figures illustrate how the dependence of E_C on black hole mass disappears when dividing the sample into bins of Eddington ratio, and that sources with $\lambda_{Edd} \geq 0.1$ tend to have lower cut-off energies than those with $\lambda_{Edd} < 0.1$, regardless of the interval of M_{BH}.

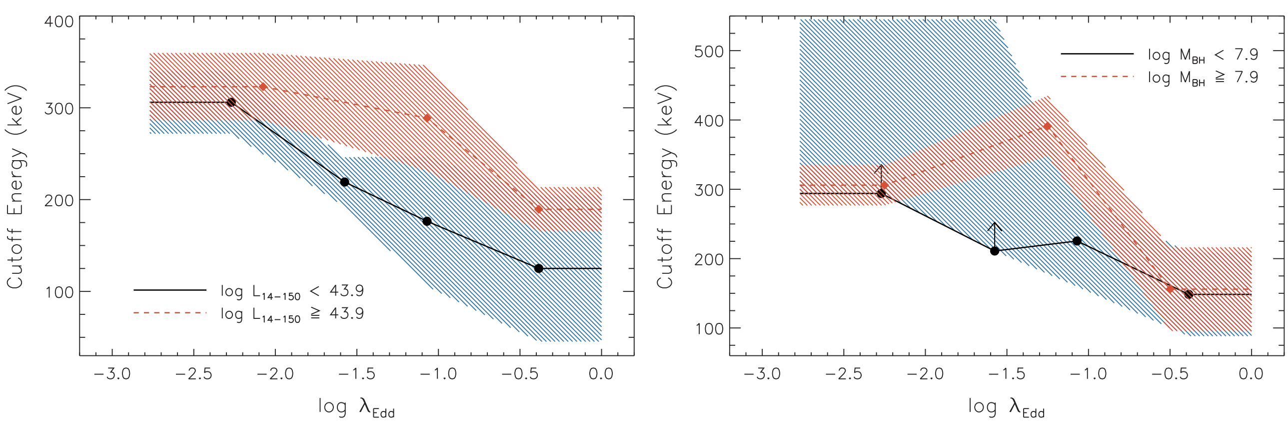

Figure 8. Cut-off energy versus the Eddington ratio for two ranges of luminosity (left-hand panel, in erg s^{-1}) and black hole mass (right-hand panel, in $M_{\odot}$). Both panels show the median cut-off energies; the shaded areas corresponds to the median absolute deviations. In the right-hand panel the first two bins of $\log (M_{BH}/M_{\odot}) < 7.9$ are lower limits because only censored data are available in that interval of λ_{Edd} and M_{BH}. The plots show that sources with $\lambda_{Edd} \geq 0.1$ tend to have lower cut-off energies than those with $\lambda_{Edd} < 0.1$, regardless of the black hole mass or luminosity, thus confirming that the Eddington ratio is the main physical parameter controlling E_C.

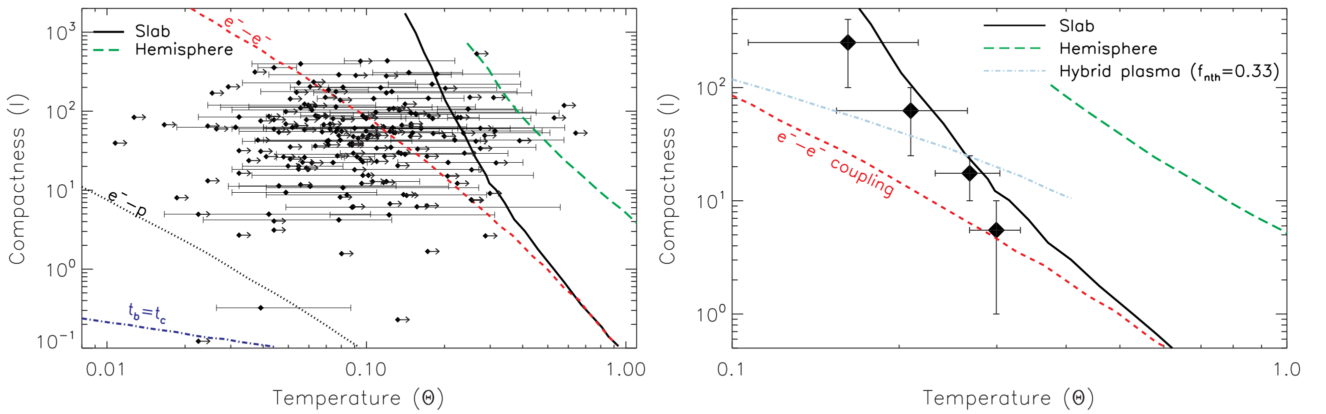

Figure 9. Left-hand panel: Compactness–temperature diagram for the 211 AGNs in our hard X-ray selected sample for which cut-off energies (Ricci et al. 2017a) and black hole masses (Koss et al. 2017) were available within BASS. The blue dot–dashed curve shows the limit of the region where bremsstrahlung dominates, while the black dotted and red dashed curves show the boundary to the region dominated by electron–proton and electron–electron coupling, respectively. The continuous black and the long dashed green curves represent the runaway pair production limits for a slab and a hemisphere corona (Stern et al. 1995). Right-hand panel: same as left-hand panel, but showing the median of the temperature parameter, obtained including the lower limits using the Kaplan–Meier estimator. The cyan dot–dot–dashed curve shows the runaway pair production limit obtained considering a hybrid plasma with 33 per cent of non-thermal electrons (Fabian et al. 2017).

which black hole masses are available, assuming $R_X = 10R_g$. Several regions can be defined in this diagram, depending on the process dominating the electron cooling (see Fabian et al. 2015 and references therein for a detailed discussion). The region where bremsstrahlung dominates the cooling of electrons is defined by $l \lesssim 3\alpha_f \Theta^{-1/2}$ (blue dot–dashed curve), where α_f is the fine-structure constant. Electron–proton and electron–electron collisions occur faster than the electron cooling for compactness and temperatures lower than the values delimited by the black dotted curve and the red dashed curve, respectively (Ghisellini, Haardt & Fabian 1993; Fabian 1994).

Pair production, due to photon–photon collisions, can be a fundamental process in coronae (Svensson 1982b,a; Guilbert et al. 1983). This process could lead to runaway pair production, acting as a thermostat for the corona (Bisnovatyi-Kogan, Zel'dovich & Syunyaev 1971; Svensson 1984; Zdziarski 1985; Fabian et al. 2015, 2017). The region where there is runaway pair production is delimited by the *pair line*, which is illustrated as a green dashed curve (following Svensson 1984) and as a black continuous curve (following Stern et al. 1995) in Fig. 9 for an isolated cloud and for a slab corona, respectively. If an X-ray source moves into this region of the parameter space (by an increase in its temperature or compactness), then it starts to rapidly form pairs, which increases the number of particles sharing the available power, causing the energy per particle (i.e. the temperature) to drop. *Sources are therefore expected to typically lie at the edge of the pair region.*

The right-hand panel of Fig. 9 shows the median values of Θ in different bins of l. The medians were calculated using the Kaplan–Meier estimator, including the lower limits, as discussed in Section 3. We also show the pair line for a hybrid plasma with 33 per cent of the electrons being non-thermal (Fabian et al. 2017). The plot illustrates that, in general, AGNs are concentrated close to the pair line corresponding to a slab, avoiding the runaway pair production region, in agreement with theoretical predictions. Since plasmas are expected to concentrate right on the edge of the relevant pair-production regions in the compactness–temperature parameter space (see above), this suggests that the shape of the X-ray corona might be better approximated as a slab rather than sphere. This would also easily explain the observed dependence of the cut-off energy on the Eddington ratio. For a fixed value of R (in R_g), ł is in fact directly proportional to the Eddington ratio ($l \propto \frac{\lambda_{Edd} R_g}{\kappa_X R}$, see equation 2), and since Θ decreases with ł, one would expect that AGNs accreting at high λ_{Edd} would also tend to have X-ray emitting plasma with lower temperatures. This is also consistent with what is found for the AGN from Fabian et al. (2015) (Fig. 10): objects at low temperature and high compactness tend to have higher λ_{Edd} (e.g. Ark 564; see Kara et al. 2017) than those at high temperature and low compactness.

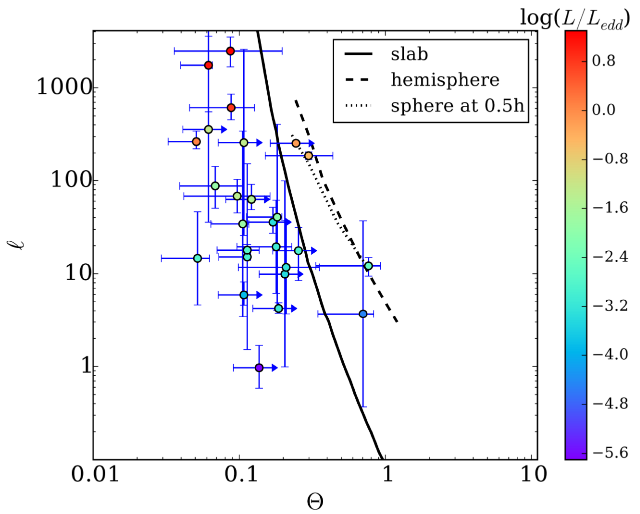

Figure 10. Temperature (Θ)–compactness (l) diagram for the AGN from Fabian et al. (2015), color-coded according to their Eddington ratio. The cut-off energy were inferred using *NuSTAR* observations. The continuous, dashed and dotted lines represent the pair lines for different geometries of the corona: a slab, a hemisphere, and a sphere at a height equal to half the radius of the sphere, respectively. Consistently with what we found for our sample, objects at low temperature and high compactness tend to have higher λ_{Edd} than those at high temperature and low compactness.

5 THE PLASMA OPTICAL DEPTH AND ITS RELATION WITH THE ACCRETION PROPERTIES OF AGNS

In this section, we explore the relation between the optical depth of the Comptonizing plasma and the properties of the accreting SMBH. While τ is not a parameter directly obtained by our broad-band X-ray spectral analysis, it can be constrained indirectly using the dependence of Γ on $kT_{\rm e}$ and τ. The photon index decreases for increasing values of the Compton parameter (y; e.g. Rybicki & Lightman 1979), which is defined as:

$$y = \max(\tau, \tau^2) \times \frac{4kT_{\rm e}}{m_{\rm e}c^2}. \quad (4)$$

To calculate the relation between 2–10 keV photon index Γ, $kT_{\rm e}$, and τ we simulated, in XSPEC (Arnaud 1996), 10 000 spectra using the COMPPS model (Poutanen & Svensson 1996) which produces X-ray spectra from Comptonization in a plasma with variable geometry, temperature, and optical depth. We assumed a slab geometry, and created a uniform grid in the ranges $0.1 \leq \tau \leq 5.1$ and $30 \leq (kT_{\rm e}/\mathrm{keV}) \leq 275$. We set the inclination angle to 45°, and only considered the primary X-ray emission, setting the reflection parameter to $R = 0$. The seed photons were produced using a multicolour disc with an inner disc temperature of 10 eV. The photon index was inferred, for each value of $kT_{\rm e}$ and τ, by fitting the simulated spectra with a power law with a simple power-law model (POW) in the 2–10 keV range, leaving both the normalization and photon index free to vary. We then fit the data with:

$$\Gamma = d + e \times \log(kT_{\rm e}) + f \times \log(\tau). \quad (5)$$

From the fit, we find $d = 2.160$, $e = -0.317$, and $f = -1.062$; the median of the absolute difference between the photon index and the value found with equation (5) is $|\Gamma - [d + e \times \log(kT_{\rm e}) + f \times log(\tau)]| = 0.04$, showing that the fit can reproduce well the data.

We can then invert equation (5) to obtain the optical depth as a function of $kT_{\rm e}$ and Γ:

$$\tau = 10^{\frac{\Gamma-d}{f}} \times (kT_{\rm e})^{-0.3}. \quad (6)$$

From our spectral analysis, we have both Γ and $kT_{\rm e} = E_{\rm C}/2$ (see Section 4), so that we can calculate τ for the 211 AGNs in our sample. The sources for which only a lower limit on $E_{\rm C}$ is available have upper limits on τ. To be consistent with the simulations, we used the photon index obtained by fitting the $E \leq 10$ keV spectrum (see Ricci et al. 2017a for details). The distribution of the plasma optical depth for our sample is shown in Fig. 11. Using ASURV, following the same approach outlined in Section 3 we find that, for the whole sample, the median optical depth is $\tau = 0.25 \pm 0.06$.

We investigated the relation between τ, the X-ray luminosity (Fig. 12), the black hole mass (Fig. 13) and the Eddington ratio (Fig. 14), and found no statistically significant correlations between these quantities. However, we find $a \simeq 3\sigma$ difference in the optical depth of objects accreting at low ($\lambda_{\rm Edd} \leq 0.1$) and at high ($\lambda_{\rm Edd} > 0.1$) Eddington ratios, with the median values being $\tau = 0.15 \pm 0.07$ and $\tau = 0.44 \pm 0.07$, respectively. If the optical depth of the corona increases with the density of the accretion disc (n), then the increase of τ with $\lambda_{\rm Edd}$ would be consistent with the classical accretion disc model (Shakura & Sunyaev 1973), according to which $n \propto \lambda_{\rm Edd}$. In a recent work, Tortosa et al. (2018a) found an anticorrelation between the temperature and the optical depth of the X-ray emitting plasma. Considering this, and the decrease of the temperature of the Comptonizing plasma with the Eddington ratio, one would naturally expect that at higher $\lambda_{\rm Edd}$ AGNs tend to preferentially have coronae with larger optical depths.

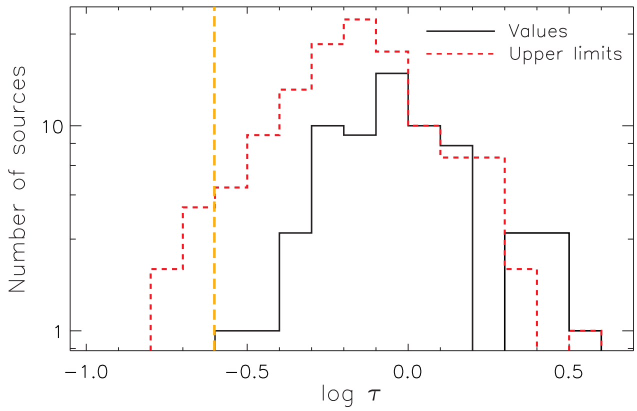

Figure 11. Histogram of the optical depth of the Comptonizing plasma, calculated using equation (6) (see Section 5). The continuous black and dashed red lines illustrate the values and the upper limits, respectively. The vertical dashed orange line shows the median of the sample ($\tau = 0.25 \pm 0.06$), calculated taking into account the upper limits.

6 THE TEMPERATURE–COMPACTNESS PLANE AND THE Γ–$\lambda_{\rm EDD}$ CORRELATION

6.1 The Γ–$\lambda_{\rm Edd}$ relation

A relation between the photon index and the Eddington ratio has been reported by several authors over the past two decades (e.g. Brandt, Mathur & Elvis 1997; Shemmer et al. 2006, 2008; Risaliti, Young & Elvis 2009; Brightman et al. 2013, 2016; Fanali et al. 2013; Kawamuro et al. 2016), which have shown that, for increasing $\lambda_{\rm Edd}$, the X-ray continuum tend to be steeper. Most of these works have found that the correlation

$$\Gamma = \psi \log \lambda_{\rm Edd} + \omega \quad (7)$$

has a slope $\psi \sim 0.3$ (e.g. Shemmer et al. 2008; Brightman et al. 2013), while a steeper slope ($\psi \simeq 0.6$) was reported by Risaliti et al. (2009), who studied SDSS quasars with archival *XMM–Newton* observations. More recently, Trakhtenbrot et al. (2017), using BASS, found instead a significantly weaker and flatter ($\psi \simeq 0.15$) correlation when using Γ obtained by considering complex spectral models (see Ricci et al. 2017a for details). Interestingly, when using Γ obtained by fitting the spectra of unobscured AGNs with a simple power law model in the 2–10 keV range, Trakhtenbrot et al. (2017) found a slope similar ($\phi = 0.30 \pm 0.09$) to that reported by previous studies. The existence of a relation between Γ and $\lambda_{\rm Edd}$ has been confirmed by repeated observations of individual sources, which have shown that the photon index increases with the flux (e.g. Perola et al. 1986; Matsuoka et al. 1990; Lamer et al. 2003; Sobolewska & Papadakis 2009). Interestingly, Sobolewska & Papadakis (2009) found that ψ differs from object to object, varying from $\simeq 0.10$ to $\simeq 0.30$, and that the slope for the average spectral slope versus the average Eddington ratio is $\psi = 0.08 \pm 0.02$. This slope is consistent with that found for BASS by Trakhtenbrot et al. (2017), and with the value reported by Ricci et al. (2013; $\psi = 0.12 \pm 0.04$) for a sample of 36 nearby AGNs, considering the average Γ and $\lambda_{\rm Edd}$. The difference between the slopes found by the works reported above is likely related to the approach used for

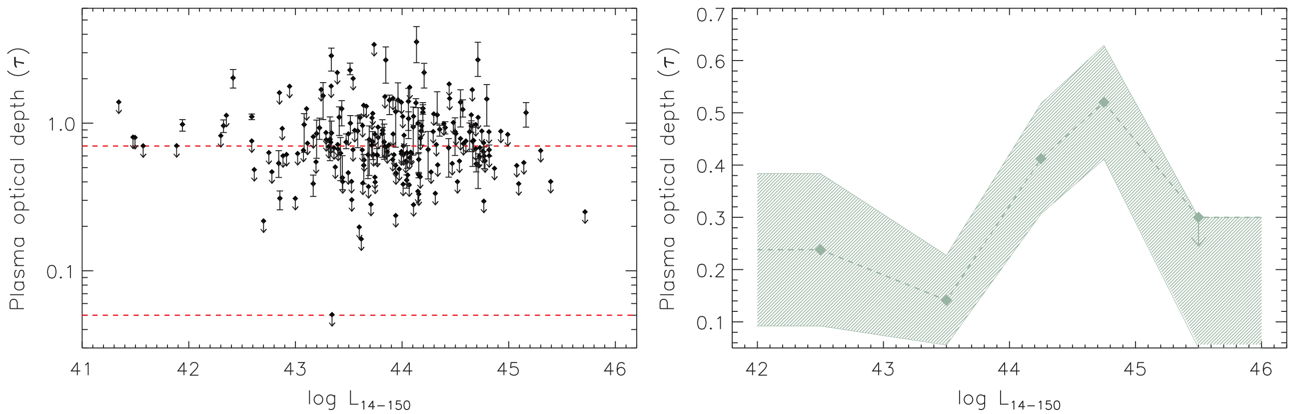

Figure 12. Left-hand panel: Optical depth versus the 14–150 keV intrinsic luminosity (in erg s^{-1}). The red dashed lines show the interval of τ shown in the right-hand panel. Right-hand panel: Median of τ for different intervals of L_{14-150}, calculated including the lower limits using the Kaplan–Meier estimator. The shaded area corresponds to the median absolute deviation.

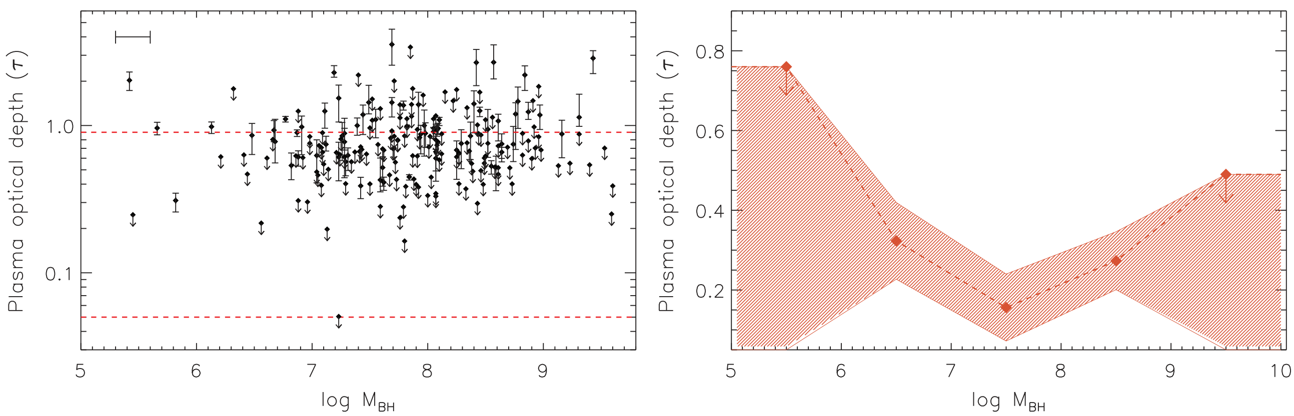

Figure 13. Left-hand panel: Optical depth versus M_{BH} (in $M_{\odot}$). The red dashed lines show the interval of τ shown in the right-hand panel. The bar in the top left corner shows the typical uncertainty of M_{BH}. Right-hand panel: Median values of τ for different intervals of M_{BH}. The shaded area represents to the median absolute deviation.

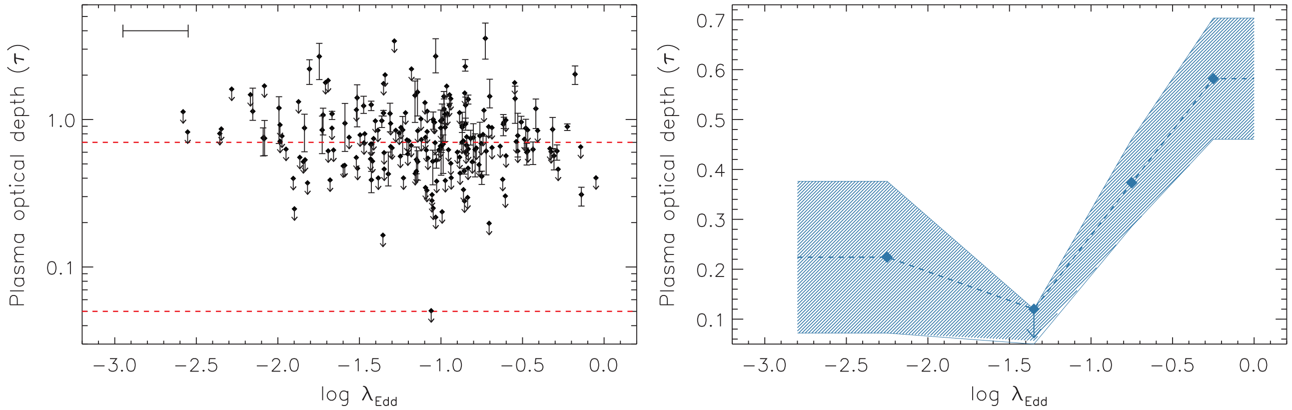

Figure 14. Left-hand panel: Optical depth of the plasma versus the Eddington ratio. The red dashed lines show the interval of τ shown in the right-hand panel. The bar in the top left corner shows the typical uncertainty of λ_{Edd}. Right-hand panel: Median values of τ for different intervals of λ_{Edd}. The shaded area corresponds to the median absolute deviation.

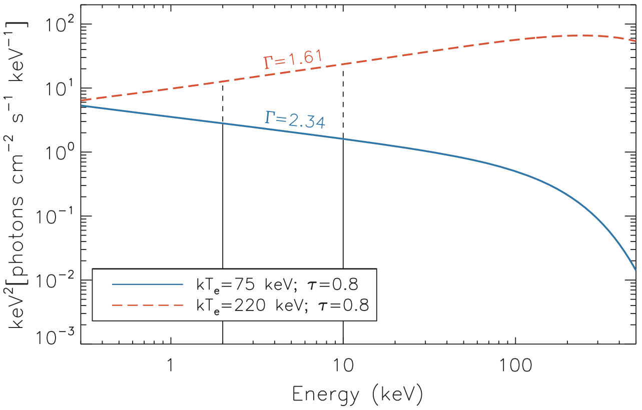

Figure 15. Comptonization X-ray spectra obtained using the COMPPS model assuming an optical depth $\tau = 0.8$, a spherical corona and different plasma temperatures: $kT_e = 75$ keV (blue continuous line) and $kT_e = 220$ keV (red dashed line). The photon indices obtained by fitting the spectra with a simple power law model in the 2–10 keV range are also reported, showing that the X-ray continuum becomes harder for higher temperatures of the corona (see Section 6).

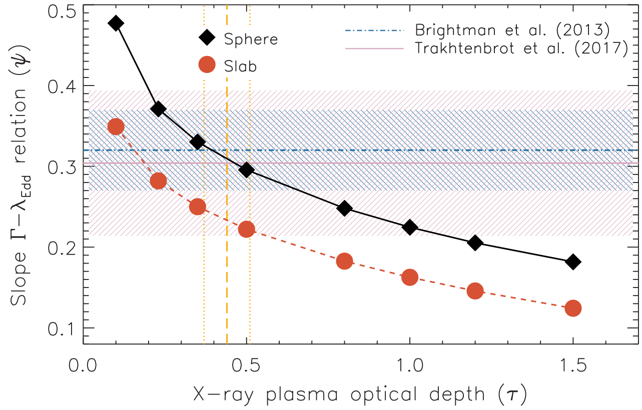

Figure 16. Slopes of the Γ–$\lambda_{\rm Edd}$ relation (ψ) obtained by simulating a population of AGNs with coronae following the pair line in the Θ–l diagram, as described in Section 6, for different values of the plasma optical depth (τ), and for two geometries of the X-ray source: sphere (black diamonds) and slab (red circles). The horizontal lines show the slopes obtained by recent works, while the shaded areas illustrate their uncertainties. The vertical orange dashed line shows the median optical depth in our sample (Section 5), while the dotted orange lines show its 1σ uncertainty. The simulations show that a temperature of the X-ray emitting plasma depending on the Eddington ratio following equations (2), (3), and (8) can reproduce the Γ–$\lambda_{\rm Edd}$ correlation for a large range of optical depths.

the spectral fitting (i.e. a simple power-law model or more complex models), to the energy band, and to the sample used.

6.2 Explaining the Γ–$\lambda_{\rm Edd}$ relation with the pair line

The physical mechanism responsible for this correlation is still debated. It has been proposed that this might be related to a more efficient cooling of the X-ray emitting plasma at higher $\lambda_{\rm Edd}$, due to the larger amount of optical and UV seed photons produced by the accretion disc (e.g. Vasudevan & Fabian 2007; Davis & Laor 2011). However, as argued by Trakhtenbrot et al. (2017), the number of optical and UV photons also increases when the black hole mass decreases (e.g. Done et al. 2012; Slone & Netzer 2012), so that one would also expect a relation between Γ and $M_{\rm BH}$, which is not observed. In previous sections, we have shown that the temperature of the Comptonizing plasma tends to decrease for increasing $\lambda_{\rm Edd}$ (Section 3), and that this effect could be related to the fact that coronae tend to concentrate around the runaway pair creation line (Section 4). This could provide an alternative mechanism for the Γ–$\lambda_{\rm Edd}$ relation, since the photon index depends on the temperature of the plasma (see Fig. 15 and equation 6).

To test whether the limits imposed by pair production on the plasma temperature for a given compactness parameter could explain the observed relation between Γ and $\lambda_{\rm Edd}$, we first interpolated the limit of the runaway pair production region in the Θ–l diagram (considering a slab corona, see Stern et al. 1995) using a polynomial of the second order:

$$\log\Theta = a + b \times \log l + c \times \log^2 l. \quad (8)$$

From the fit, we obtained $a= -0.282164$, $b= -0.239618$, and $c= 0.0215106$. We then assumed that typically coronae are distributed along this line, as shown in the right-hand panel of Fig. 9. We simulated 10 000 spectra using COMPPS, similarly to what was done in Section 5. We set the plasma temperature kT_e to depend on the Eddington ratio by combining equations (2) and (3) with equation (8), i.e. transforming the $\Theta(l)$ relation into a $kT(\lambda_{\rm Edd})$ function:

$$\log(kT_e) = a_1 + b \times \log(\eta\lambda_{\rm Edd}) + c \times \log^2(\eta\lambda_{\rm Edd}), \quad (9)$$

where $a_1 = a + \log(m_e c^2)$ and $\eta = \frac{\pi m_p}{50 m_e}$, assuming $R_X = 10\,R_g$ and $\kappa_x = 20$. We explored a range in Eddington ratio between 10^{-3} and 1, which translates into a plasma temperature interval of $kT_e =$ 220–73 keV. We explored a range of Comptonizing plasma optical depths (τ), from 0.1 to 1.5, and two different geometries of the corona (sphere and slab). In Fig. 15, we show, as an example, two spectra obtained with COMPPS, assuming the parameters reported above, an optical depth of $\tau = 0.8$ and plasma temperatures of $kT_e = 220$ keV (red dashed line) and $kT_e = 75$ keV (blue continuous line), which encompass the range of temperature explored in our simulations. The figure clearly shows that cooler plasma tend to create significantly steeper X-ray spectra in the 2–10 keV range.

The simulated spectra were then fit with a power-law model in the 2–10 keV range. We studied the relation between Γ and $\lambda_{\rm Edd}$, fitting the data with an expression that follows equation (7). As shown in Fig. 16, the fact that coronae follow the pair line could easily reproduce the observed slope of the Γ–$\lambda_{\rm Edd}$ correlation. In the figure, we use the value of ϕ from Trakhtenbrot et al. (2017) inferred using the photon index obtained by applying a simple power-law model to the 2–10 keV spectrum, consistently with what was done for our simulations. The optical depth extrapolated from our sample in Section 5 would correspond to slopes in the range $\psi \simeq 0.26$–0.30, in agreement with the observations (orange vertical lines in Fig. 16). The steeper slopes of the correlation obtained for optically thinner plasma are likely due to the stronger influence of changes in temperatures on the X-ray spectrum. The large scatter observed in the Γ–$\lambda_{\rm Edd}$ correlation (e.g. Ho & Kim 2016; Trakhtenbrot et al. 2017) could be ascribed to several causes, such as the intrinsic scatter in the Θ–l diagram, different optical depths of the Comptonizing region, and/or different sizes and geometries of the corona. Moreover, pair production in non-thermal plasma could create a large range of plasma temperatures (Fabian et al. 2017), which would also contribute to the scatter.

7 SUMMARY AND CONCLUSION

We have studied here the relation between the coronal and accretion properties of 211 local unobscured AGNs from the BAT AGN Spectroscopic Survey. The main findings of our work are the following.

(i) The median temperature of the X-ray emitting plasma for the objects in our sample is $kT_e = 105 \pm 18$ keV.

(ii) The main parameter driving the cut-off energy is the Eddington ratio (see Section 3, Fig. 4 and Fig. 8). This is shown by the negative correlation between E_C and λ_{Edd} (Fig. 4), and by the fact that any trend with luminosity or black hole mass disappears when dividing the samples into bins of λ_{Edd}, while the difference between low and high Eddington ratio sources is always observed, regardless of the interval of luminosity (right-hand panel of Fig. 6) or black hole mass (right-hand panel of Fig. 7).

(iii) At low Eddington ratios ($\lambda_{Edd} \leq 0.1$), the median cut-off energy is $E_C = 370 \pm 51$ keV, while at high Eddington ratios ($\lambda_{Edd} > 0.1$) is $E_C = 160 \pm 41$ keV, which implies a 3.2σ difference between the two subsamples.

(iv) We studied the distribution of the AGN in our sample in the temperature–compactness ($\Theta - l$) parameter space (Section 4), and found that AGNs typically tend to avoid the pair runaway region, and to lie between the e^-–e^- coupling line and the pair line for a slab corona (equation 8), implying that the geometry of the corona may be better described as a slab (instead of a sphere).

(v) The relation between E_C and λ_{Edd} can be explained by the fact that AGNs tend to avoid the pair runaway region in the $\Theta - l$ diagram, considering that, for a fixed size of the X-ray emitting region, the compactness is proportional to the Eddington ratio ($l \propto \lambda_{Edd}$, see equation 2).

(vi) Using spectral simulations, considering a slab corona, we show that the optical depth of the Comptonizing plasma can be calculated from Γ and E_C using equation (6) (see Section 5). The median value of the optical depth for our sample is $\tau = 0.25 \pm 0.06$, and objects accreting at $\lambda_{Edd} \leq 0.1$ have a lower median optical depth ($\tau = 0.15 \pm 0.07$) than those with $\lambda_{Edd} > 0.1$ ($\tau = 0.44 \pm 0.07$).

(vii) Simulating AGN populations with an X-ray spectral Comptonization model, we showed that Comptonizing plasma with temperatures and compactness lying along the pair line can straightforwardly reproduce the observed slope of the Γ–λ_{Edd} relation (see Section 6).

BASS aims to reliably estimate, in the near future, black hole masses for about 1000 local AGNs. Therefore, future studies of a larger number of hard X-ray selected AGNs carried out with *Swift*/BAT and *NuSTAR* (in the framework of the BAT legacy survey), will be able to better characterize the relation between the cut-off energy and the Eddington ratio, and to understand the importance of non-thermal components in the X-ray emitting plasma.

ACKNOWLEDGEMENTS

We thank the reviewer for the useful comments, which helped us improve the quality of the manuscript. This work made use of data from the NASA/IPAC Infrared Science Archive and NASA/IPAC Extragalactic Database (NED), which are operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. We acknowledge financial support from the National Key R&D Program of China grant No. 2016YFA0400702 (LH), the National Science Foundation of China grants no. 11473002 and 1721303 (LH), FONDECYT 1141218 (CR, FEB), FONDECYT 1160999 (ET), CONICYT PIA ACT172033 (ET), Basal-CATA PFB–06/2007 (CR, FEB, ET), the China-CONICYT fund (CR), the CONICYT+PAI Convocatoria Nacional subvencion a instalacion en la academia convocatoria año 2017 PAI77170080 (CR), the Swiss National Science Foundation (Grant PP00P2_138979 and PP00P2_166159, KS), the Swiss National Science Foundation (SNSF) through the Ambizione fellowship grant PZ00P2_154799/1 (MK), the NASA ADAP award NNH16CT03C (MK), the ERC Advanced Grant Feedback 340442 (ACF), and the Ministry of Economy, Development, and Tourism's Millennium Science Initiative through grant IC120009, awarded to The Millennium Institute of Astrophysics, MAS (FEB). This work was partly supported by the Grant-in-Aid for Scientific Research 17K05384 (YU) from the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT).

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