THE INTEGRAL HIGH-ENERGY CUT-OFF DISTRIBUTION OF TYPE 1 ACTIVE GALACTIC NUCLEI

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\section{ABSTRACT}

In this Letter we present the primary continuum parameters, the photon index $\Gamma$, and the high-energy cut-off $E_c$ of 41 type-1 Seyfert galaxies extracted from the \textit{International Gamma-Ray Astrophysics Laboratory} (\textit{INTEGRAL}) complete sample of active galactic nuclei (AGNs). We performed broadband (0.3–100 keV) spectral analysis by simultaneously fitting the soft and hard X-ray spectra obtained by \textit{XMM} and \textit{INTEGRAL}/IBIS–\textit{Swift}/BAT, respectively, in order to investigate the general properties of these parameters, in particular their distribution and mean values. We find a mean photon index of 1.73 with a standard deviation of 0.17 and a mean high-energy cut-off of 128 keV with a standard deviation of 46 keV for the whole sample. This is the first time that the cut-off energy is constrained in such a large number of AGNs. We have 26 measurements of the cut-off, which corresponds to 63% of the entire sample, distributed between 50 and 200 keV. There are a further 11 lower limits mostly below 300 keV. Using the main parameters of the primary continuum, we have been able to obtain the actual physical parameters of the Comptonizing region, i.e., the plasma temperature $kT_e$ from 20 to 100 keV and the optical depth $\tau < 4$. Finally, with the high signal-to-noise ratio spectra starting to come from \textit{NuSTAR} it will soon be possible to better constrain the cut-off values in many AGNs, allowing the determination of more physical models and thus better understand the continuum emission and geometry of the region surrounding black holes.

\textit{Key words:} galaxies: active – gamma rays: galaxies – X-rays: galaxies

\section{1. INTRODUCTION}

The advent of high-energy observatories like the \textit{International Gamma-Ray Astrophysics Laboratory} (\textit{INTEGRAL}) and \textit{Swift} has provided greater depth to the study of active galactic nuclei (AGNs), as they provide information on spectral features that cannot be explored without observations performed above 10 keV. The high-energy data are crucial not only to estimate the slope of the continuum emission over a wide energy band but also to measure the high energy cut-off and the reflection fraction, which are important physical parameters.

First, they are important parameters for evaluating the AGN contribution to the cosmic X-ray background (CXB); indeed, while the fraction of CXB resolved into discrete sources is determined 100% below 2–10 keV and 50% in the 7–10 keV band, it becomes negligible at higher energies, i.e., above 10 keV, just where its spectral intensity peaks at around 30 keV. In order to reproduce the shape of the CXB, synthesis models (e.g., Comastri et al. 2005) use several parameters such as the fraction of heavily obscured sources, the so-called Compton-thick AGN characterized by $N_H \geq 10^{24}$ cm$^{-2}$, the coverage and the geometry of the cold gas distributed around the black hole responsible for the reflection hump, and the high-energy cut-off of the primary continuum emission, which is not well determined. Recently, to estimate the AGN contribution to the CXB, several models which take into account the average power-law photon index (and its standard deviation in values) and the spread of the average cut-off energy instead of the single mean values have been proposed (Gandhi et al. 2007; Gilli et al. 2007; Comastri 2004). Therefore, the determination of photon indices and cut-off energies, their mean values, and their distributions over a wide sample of sources, covering a wide range of energies (above 100 keV), is essential to obtain a much firmer estimate of the AGN contribution to the CXB high energy.

Measuring the slope of the continuum emission and the high-energy cut-off of AGNs is also important because both parameters enable us to understand the physical characteristics and the geometry of the region around the central nucleus. AGN spectral models that focus on the reproduction of the observed shape of the primary continuum ascribe a power law to the inverse Compton scattering of soft photons off hot electrons located above the accretion disk in the so-called corona (Maraschi & Haardt 1997; Zdziarski 1998). In the framework of this disk–corona system, the temperature $kT_e$ and the optical depth $\tau$ of the scattering electrons mainly determine the spectral slope, while the cut-off energy is related essentially to $kT_e$, and thus simultaneous measurements of $\Gamma$ and $E_c$ allow us to understand the physical parameters of the Comptonizing region. The more accurate the measurements of these parameters, the better we can determine the geometry and the physical properties of the inner region of AGNs.

Several studies have been carried out to specify the distribution of photon indices in the soft 2–10 keV (Bianchi et al. 2009) and hard 20–100 keV X-ray bands (Molina et al. 2013) while, after early results coming in the 1990s from \textit{BeppoSAX}, which had a broad spectral coverage (2–100 keV), measurements of high energy cut-offs have been limited by the scarcity of observations above 10 keV.

With the launch of \textit{INTEGRAL} and \textit{Swift} the number of AGNs detected above 10 keV has grown enormously, but to properly measure the high energy cut-off, a broadband spectral study is needed. This implies that both low- and high-energy spectra have to be fitted simultaneously, employing spectra with high statistical quality such as those acquired, for example, with \textit{XMM} and \textit{INTEGRAL}. It has been demonstrated (Molina et al. 2009; de Rosa et al. 2012; Panessa et al. 2011) that the match between \textit{XMM} and \textit{INTEGRAL} spectra is good, with the cross-calibration constant between the two instruments around 1. Therefore, when a constant different from unity is found, this
generally indicates flux variations between the soft and the hard X-ray domain.

In this Letter, we report on the high-energy cut-off measurements and their distribution, derived from the analysis of XMM plus INTEGRAL/IBIS and Swift/Burst Alert Telescope (BAT) data of all 41 Seyfert 1 galaxies out of the 88 sources listed in the INTEGRAL complete sample of AGNs (Malizia et al. 2009).

2. BROADBAND SPECTRAL ANALYSIS

In this work, we have performed 0.3–100 keV spectral analysis of all type 1 Seyfert galaxies included in the INTEGRAL complete sample of AGNs, excluding only five narrow line Seyfert 1 galaxies that were extensively studied by Panessa et al. (2011). For all 41 AGNs we have collected XMM observations in the soft band and INTEGRAL/IBIS plus Swift/BAT observations in the hard X-ray domain.

EPIC-pn Turner et al. (2001) data were processed using the XMM Standard Analysis Software version 12.0.1 employing the latest available calibration files and following the spectral data reduction as in Molina et al. (2009). Since our sources are bright in X-ray, several were affected by pile-up and for these only patterns corresponding to single events (PATTERN = 0) were considered. The INTEGRAL data reported here consist of ISGRI data from several pointings between revolutions 12 and 530, i.e., those coming from the fourth IBIS catalog (Bird et al. 2010). ISGRI data analysis and the average source spectra extraction has been obtained following the procedure described by Molina et al. (2013). The Swift/BAT spectra (Baumgartner et al. 2013), taken in order to improve the statistics at high energies, are from the latest 70 month catalog. IBIS and BAT analysis were performed in the 20–100 keV and 14–100 keV bands, respectively.

It is worth noting that the broadband spectral analysis of a large fraction of our objects has been previously reported in Molina et al. (2009), but XMM and/or Swift/BAT data were available at that time only for a limited number of AGNs and the rest had a significantly poorer spectral quality at low energies. For three sources (NGC 3783, IC 4329A, and IGR J21247−5058), we do not perform new spectral fitting; the values in Molina et al. (2009) are used. This is due to the fact that (1) we already had good constraints on the spectral shape and (2) the data have been recently confirmed by Suzaku (NGC 3783: Brenneman et al. 2011; Patrick et al. 2011; IGR J21247−5058: Tazaki et al. 2010) and NuSTAR (Harrison et al. 2013; IC 4329A: Brenneman et al. 2014).

We simultaneously fitted the soft and the hard X-ray spectra obtained by XMM and INTEGRAL/IBIS–Swift/BAT in the 0.3–100 keV energy range, using XSPEC v.12.8.0, with errors quoted at the 90% confidence level for one parameter of interest ($\Delta \chi^2 = 2.71$). To fit the 0.3–100 keV continuum, we considered a baseline model commonly used to fit broadband X-ray spectra, composed of a power law with an exponential cut-off reflected from neutral matter (PexraV model in XSPEC), where $R$, defined as $\Omega/2\pi$, is the parameter that corresponds to the reflection component. Since we are analyzing type 1 sources, we have assumed a face-on geometry and fixed the inclination angle of the reprocessor to 30°.

At soft energies, Galactic absorption has always been considered and, when required by the data, intrinsic absorption in terms of simple or/and complex, cold, or ionized absorbers has been added (WABS, PCfabs, ZKIPCF). Since the low-energy part of type 1 AGN spectra often shows clear signs of a soft excess, this has been generally fitted with a thermal component (BREMS) when present. A Gaussian component has also been included, to take into account the presence of the iron Kα line at around 6.4 keV; in a few cases, residuals around 7 keV have also been fitted adding a second Gaussian line to take into account the iron Kβ feature. Finally, to take into consideration possible flux variations between instruments, we have introduced cross-calibration constants, which we left free to vary, keeping in mind that possible miscalibration between XMM and IBIS or BAT could mimic or hide the Compton reflection component above 10 keV (de Rosa et al. 2012). In the cases of NGC 4151, NGC 4593, and 4C 74.26, the fit has been performed over a more restricted energy range (2–100 keV) in order to avoid complications due to low energy features, such as the complex warm absorber, whose treatment is beyond the scope of this work. Here we focus on the primary continuum parameters, i.e., photon index and cut-off energy and to properly interpret these results we also report the low energy components (soft-excess and absorption). For completeness we list calibration constants and goodness of fit (see Table 1). Since the primary aim of the present Letter is to study the cut-off measurements and to determine their distribution, we will not report all of the spectral parameters, such as the reflection fraction and iron line features, and defer to an upcoming work the discussion on the spectral complexity of each type 1 AGN of the INTEGRAL complete sample.

As shown in the table, there are six sources where, in order to have a good broadband fit, it has been necessary to fix the photon index to the best fit value found using the XMM data alone; in five of them both the values of the BAT and IBIS cross-calibration constants are consistent with unity, indicating that the continuum shape at energies above 20 keV is consistent with that in the 2–10 keV band. Instead, in LEDA 168,563 the cross-calibration constant between XMM and BAT is in the range (0.53–0.65), probably due to the variability of the source at high energy as the difference between the BAT and IBIS 20–100 keV fluxes suggests ($F_{\text{BAT}} = 3.8 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ and $F_{\text{IBIS}} = 5.3 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$). For B3 0309+411B and IGR J18027−1455, we have used only the BAT data for the 20–100 keV band, since the former source has been detected by IBIS in a burst map (see Bird et al. 2010) and the latter has been found to be extremely variable (see Molina et al. 2009); in both cases, the extrapolation of the high energy spectrum from the 2–10 keV band gave a source status more consistent with the BAT measurement and hence we chose not to use the IBIS data. Only for IGR J18249−3243 is there no BAT observation available; moreover, this source has also been detected by IBIS by means of burst analysis, so the overall ISGRI spectrum, extracted from the fourth IBIS catalog, is of very poor quality (~3σ). Therefore for this source the spectral parameter values should be taken with some caution. Care should also be used for IGR J16119−6039, as this galaxy is inside the Norma Cluster (A3627) and thus, as already pointed out by Ajello et al. (2010), we should expect contamination from the cluster thermal emission in the high energy spectrum of this source.

3. RESULTS

In Table 1 we report the fit results only for the spectral parameters that are of interest in this work; the goodness of our fits (see the last column in the table) is expressed in terms of reduced $\chi^2$ and, as a further indication, we also report the

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4 http://swift.gsfc.nasa.gov/results/bs70mon/
### Table 1: Main Spectral Parameters

| Source          | $kT$ (keV) | $N_{H}^{IC}$ ($\times 10^{22}$ cm$^{-2}$) | $N_{H}^{IC}$ (cf) | $N_{H}^{IC}$ (log $\xi$ − cf) ($\times 10^{22}$ cm$^{-2}$) | $\Gamma$ | $E_{c}$ | $C_{BAT}$ | $C_{BHS}$ | $\chi^{2}$ (dof) |
|-----------------|-----------|------------------------------------------|-------------------|----------------------------------------------------------|---------|--------|----------|----------|-----------------|
| IGR J0033+6122  | 1.66$^{+0.35}_{-0.30}$ | ... | ... | ... | 1.50$^{+0.32}_{-0.09}$ | >52 | 0.88$^{+0.22}_{-0.41}$ | 1.29$^{+0.42}_{-0.09}$ | 3883.8 (365) |
| QSO B0241+62   | 0.14$^{+0.06}_{-0.05}$ | ... | ... | ... | 1.74$^{+0.12}_{-0.09}$ | >138 | 1.15$^{+0.30}_{-0.26}$ | 1.02$^{+0.31}_{-0.26}$ | 394.4 (492) |
| B3 0309+411    | ... | ... | ... | ... | 1.81$^{+0.04}_{-0.04}$ | ... | 1.64$^{+0.80}_{-0.56}$ | ... | 421 (424) |
| 3C 111          | 0.38$^{+0.01}_{-0.01}$ | ... | ... | ... | 1.62$^{+0.02}_{-0.02}$ | 136$^{+47}_{-39}$ | 0.60$^{+0.07}_{-0.08}$ | 0.87$^{+0.17}_{-0.19}$ | 1069.6 (1028) |
| LEDA 168563     | 0.37$^{+0.01}_{-0.02}$ | ... | ... | ... | 1.70 (fixed) | 177$^{+144}_{-138}$ | 0.59$^{+0.06}_{-0.06}$ | 0.80$^{+0.19}_{-0.19}$ | 1495 (1327) |
| 4U0517+17       | 0.10$^{+0.03}_{-0.04}$ | ... | ... | 65.0$^{+34}_{-35}$ (2.5 fixed − 0.24 ± 0.12) | 1.78 (fixed) | 175$^{+78}_{-74}$ | 1.10$^{+0.12}_{-0.13}$ | 1.10$^{+0.16}_{-0.16}$ | 1800.3 (1634) |
| MCG+08-11-011   | ... | ... | ... | ... | 1.79$^{+0.01}_{-0.01}$ | 171$^{+64}_{-50}$ | 0.56$^{+0.13}_{-0.13}$ | 0.52$^{+0.13}_{-0.13}$ | 1364.7 (1402) |
| Mkr 6           | ... | ... | ... | ... | 1.54$^{+0.14}_{-0.13}$ | 131$^{+132}_{-128}$ | 1.00$^{+0.20}_{-0.23}$ | 1.04$^{+0.33}_{-0.28}$ | 1276 (1283) |
| IGR J07597−3842 | 0.16$^{+0.01}_{-0.02}$ | ... | ... | ... | 1.58$^{+0.04}_{-0.03}$ | 79$^{+24}_{-16}$ | 0.86$^{+0.22}_{-0.15}$ | 0.98$^{+0.29}_{-0.20}$ | 286.7 (282) |
| ESO 209−12      | 0.11$^{+0.01}_{-0.02}$ | ... | ... | ... | 1.60$^{+0.05}_{-0.03}$ | 135$^{+302}_{-259}$ | 0.90$^{+0.23}_{-0.19}$ | 1.68$^{+0.38}_{-0.34}$ | 597.1 (534) |
| FRL 1146        | 0.15$^{+0.01}_{-0.01}$ | 0.32$^{+0.06}_{-0.06}$ | ... | ... | 1.74$^{+0.12}_{-0.11}$ | 84$^{+29}_{-30}$ | 0.89$^{+0.09}_{-0.09}$ | 0.97$^{+0.12}_{-0.12}$ | 421 (386) |
| Swift J0917.2−6221 | 0.09$^{+0.02}_{-0.05}$ | 2.74$^{+0.20}_{-0.16}$ (0.82 ± 0.02) | ... | ... | 1.60$^{+0.08}_{-0.08}$ | 68$^{+43}_{-41}$ | 1.82$^{+0.20}_{-0.16}$ | 1.60$^{+0.44}_{-0.47}$ | 759 (759) |
| Swift J1316.3−4942 | ... | 7.11$^{+4.92}_{-6.17}$ (0.68 ± 0.16) | ... | ... | 1.70$^{+0.22}_{-0.20}$ | >114 | 1.25$^{+0.45}_{-0.47}$ | 1.82$^{+0.87}_{-0.82}$ | 186.8 (178) |
| NGC 3783        | 1.16$^{+0.37}_{-0.27}$ | ... | ... | ... | 1.74$^{+0.09}_{-0.09}$ | 98$^{+29}_{-19}$ | 0.65$^{+0.11}_{-0.10}$ | 0.93$^{+0.28}_{-0.22}$ | 1605.3 (1768) |
| NGC 4151        | ... | 6.58$^{+0.33}_{-0.35}$ (0.87 ± 0.01) | ... | ... | 1.61$^{+0.04}_{-0.04}$ | 196$^{+57}_{-46}$ | 0.40$^{+0.01}_{-0.01}$ | 0.37$^{+0.04}_{-0.04}$ | 1580 (1444) |
| Mkr 50          | 2.24$^{+1.01}_{-0.48}$ | ... | ... | ... | 2.04$^{+0.02}_{-0.02}$ | >89 | 1.39$^{+0.72}_{-0.67}$ | 1.56$^{+0.27}_{-0.83}$ | 753.5 (763) |
| NGC 4593        | ... | ... | ... | ... | 2.02$^{+0.02}_{-0.02}$ | ... | >94 | 1.88$^{+0.76}_{-0.81}$ | 1.57$^{+0.27}_{-0.83}$ | 753.5 (763) |
| IGR J12415−5750 | ... | ... | ... | ... | 1.88$^{+0.03}_{-0.03}$ | ... | >357 | 1.17$^{+0.30}_{-0.23}$ | 0.83$^{+0.41}_{-0.43}$ | 300 (318) |
| IGR J1310−5552  | ... | ... | ... | ... | 1.88$^{+0.03}_{-0.03}$ | ... | >357 | 1.17$^{+0.30}_{-0.23}$ | 0.83$^{+0.41}_{-0.43}$ | 300 (318) |
| MCG+06-30-15    | ... | ... | ... | ... | 1.44$^{+0.05}_{-0.06}$ | 61$^{+24}_{-21}$ | 1.22$^{+0.19}_{-0.19}$ | 1.34$^{+0.29}_{-0.25}$ | 1112 (1078) |
| 4U 1344−60      | 0.93$^{+0.15}_{-0.18}$ | 4.74$^{+1.69}_{-1.36}$ (0.53 ± 0.08) | ... | ... | 1.80$^{+0.21}_{-0.21}$ | >101 | 0.61$^{+0.13}_{-0.12}$ | 0.68$^{+0.16}_{-0.16}$ | 644.3 (604) |

Notes: Error quotes at 90% confidence level for one interesting parameter.

- $N_{H}^{IC}$ refers to the cold absorption fully covering the source.
- $N_{H}^{IC}$ refers to the cold absorption(s) partially covering the nucleus, with cf being the covering fraction.
- $N_{H}^{IC}$ refers to the warm absorption, log $\xi$ is the ionization parameter, and cf is the covering fraction.
- Soft excess fitted with a power law of $\Gamma = 2.5$. 

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values of the two cross-calibration constants between XMM and BAT and between XMM and IBIS, which are generally both close to unity, with the exception of a few variable sources (e.g., NGC 4151, MCG+08-11-011).

In this Letter we report and discuss the general properties of the primary continuum parameters, photon index, and high-energy cut-off, for a large number of type 1 AGNs. We calculated their average values using the arithmetic mean and study their distribution using the standard deviation.\(^5\) We choose to adopt this simple approach because of the extreme non-Gaussianity of the data points and their asymmetric errors, which can be ignored in our analysis. Figure 1 shows the distribution of photon indices of the entire sample. The solid line at \(\Gamma = 1.73\) represents their mean value, while the dashed lines indicate the relative spread of 0.17. This mean value is consistent with that previously found in Molina et al. (2009) (\(\langle \Gamma \rangle = 1.72\), spread 0.2) and with the mean photon index of \(\langle \Gamma \rangle = 1.73\) (spread 0.45) obtained for 156 radio-quiet, X-ray unobscured AGNs analyzed in the 2–10 keV band for the XMM–CAIXA catalog by Bianchi et al. (2009).

It is worth noting that the XMM–CAIXA is the catalog most compatible with our sample as it contains bright AGNs similar to ours; furthermore, it must be emphasized that their mean photon index value has been obtained assuming the presence of the reflection component, as done in our work. It is clear from the figure that the majority of sources fall in the range 1.4–2.1 and that the mean photon index is slightly flatter than 1.9 which is the standard value generally assumed for type 1 AGNs.

Of the 41 type 1 AGNs analyzed in this work, we have been able to constrain the cut-off energy in 26 of them, which corresponds to ~63% of the entire sample. In four sources (B3 0309+411B, NGC 4593, 2E 1739.11210, and IGR J18249–3243) the cut-off energy is found at energies much higher than the IBIS/BAT bandpass and so could not be estimated; for the remaining 11 sources only lower limits are available. Figure 2 represents the main result of the present work, as it shows the distributions of \(E_c\). The mean value of the cut-off energy is 128 keV with a spread of 46 keV and its distribution ranges from 50 keV to 200 keV, confirming the previous results of Molina et al. (2009). Also the majority of the lower limits are below 300 keV with only a few exceptions (IGR J13109–5552, IGR J17488–3253, and MCG–02-58-022). The few lower limits found above 300 keV indicate that higher cut-off energies may be present but only in a small number of AGNs. However, as we only have data up to 100 keV these lower limits resulting from the fits must be treated with some caution. It is clear that the cut-off energy in type 1 AGNs has a mean value lower than previously found (e.g., Dadina 2008) and more in line with the first results coming from NuSTAR (see Matt\(^6\) and Brenneman et al. 2014).

We can use the results on photon indices and cut-off energies to test a possible correlation between them. In the past a trend of \(E_c\) increasing with \(\Gamma\) steepening has been found (Matt 2001; Petrucci et al. 2001), but it is still debated since it is well known that a degeneracy exists between the photon index and the high-energy cut-off in the spectral model employed. The high-energy cut-offs measured for our sample are plotted against their respective photon indices in Figure 3, but no evident trend is found between these two quantities. This has also been confirmed by using the Pearson statistical test on the two sets of data. The test returns a low correlation coefficient of \(r \sim 0.16\)\(^7\) (if upper limits are ignored \(r = 0.12\)); we point out that the errors on the parameters are not considered in this test. The lack of any correlation between the primary continuum parameters

\(^5\) Lower limits have not been considered in this evaluation.

\(^6\) http://astro.u-strasbg.fr/~goosmann/gAstronomy_BH_Accretion/Session_1/session1_talk_matt.pdf

\(^7\) The square of the correlation coefficient \(r\) is normally used as a measure of the association between two variables.
indirectly tests the results of our data analysis, confirming that the parameter degeneracy does not affect our fitting procedure.

Finally, in order to show the goodness of our fit, in Figure 4 we plot the cross-calibration constants between XMM and BAT ($C_{BAT}$) versus XMM and IBIS ($C_{IBIS}$). The good match between the two cross-calibration constants is quite clear, despite the fact we would have expected some variations between $C_{BAT}$ and $C_{IBIS}$ since both data sets were averaged over different observation time. This confirms that long term variability is not so common at high energies in type 1 AGNs (Beckmann et al. 2007). We found mean values of 0.97 with a spread of 0.31 and 1.07 with spread of 0.33 for $C_{BAT}$ and $C_{IBIS}$, respectively.

4. DISCUSSION

In the present work we have been able to determine the main parameters of the primary continuum: $\Gamma$ and $E_c$. Following Petrucci et al. (2001), within this scenario, we can obtain the actual physical parameters of the Comptonizing region from these spectral components. The plasma temperature $kT_e$ is estimated to be $kT_e = E_c/2$, when the optical depth $\tau < 1$, while for $\tau \gg 1$ $kT_e = E_c/3$ would be more correct. Using the following relation from Petrucci et al. (2001)

$$\Gamma - 1 \simeq \left\{ \frac{9}{4} + \frac{m_e c^2}{kT_e \tau (1 + \tau/3)} \right\}^{1/2} - \frac{3}{2}$$

and knowing the temperature, we can calculate the optical depth assuming that the spectral index derived from the PEXRAV fit. We have previously estimated that the mean value of $E_c$ for our sources is $\sim 130$ keV, ranging from 50 to 200 keV; note that higher cut-off energies may be present but only in a small number of AGNs, as also indicated by some of the lower limits found. Taking into account the most likely range of $E_c$ estimated for our sample, we have derived the most probable range of plasma temperatures $kT_e$, which is from 20 to 100 keV (or $2\times10^8$ K). Assuming our average value of $\Gamma = 1.73$ and solving the equation for both low and high values of $\tau$ and $E_c$, we get obtain acceptable solutions for $\tau$ in the range from 1 to 4.

These results are in good agreement with those previously found by Petrucci et al. (2001) for a small sample of Seyfert 1 galaxies and with those found by Molina et al. (2009) and indicate that the plasma has a typical temperature of $(50 \pm 30)$ keV and an optical depth of $\tau < 4$.

Our findings on the high energy cut-off are consistent with the synthesis models of the CXB which often assume an upper limit of $\sim 200$ keV. This assumption is essentially determined by the intensity and shape of the CXB spectrum above 20–30 keV, which cannot be exceeded. In fact if one uses a value of $E_c$ of 300 keV it becomes difficult to accommodate all available observations and CXB measurements (Gilli et al. 2007).

5. CONCLUSIONS

In this work we presented the broadband spectral analysis of 41 type 1 AGNs of the INTEGRAL complete sample by fitting together XMM, Swift/BAT, and INTEGRAL/IBIS data in the 0.3–100 keV energy band. We found that the mean photon index is 1.73 (standard deviation of 0.17) confirming previous results from XMM and INTEGRAL. The main result of this work is that for the first time we provide the high-energy cut-off distribution for a large sample of type 1 AGNs: 26 objects out of 41 analyzed, which corresponds to 63% of the sample. We found a mean value of $E_c$ of 128 keV with a spread of 46 keV indicating that the primary continuum typically decays at much lower energies than previously thought. We note that this mean value is in line with the synthesis models of the cosmic diffuse background, which often assume an upper limit of $\sim 200$ keV and emphasize that some of the same cut-off measurements reported here are now being confirmed by NuSTAR (Brenneman et al. 2014). It is worth noting that NuSTAR will be hugely advantageous for this science with its high signal-to-noise ratio (S/N), but only for sources with a relatively low cutoff, i.e., $\lesssim 150$ keV or so. The precision of the measurement of a rollover above this energy would be huge for this science with its high signal-to-noise ratio (S/N), but only for sources with a relatively low cutoff, i.e., $\lesssim 150$ keV or so. The precision of the measurement of a rollover above this energy
would be compromised due to NuSTAR’s lack of effective area above 79 keV. From the primary continuum parameters we have indirectly estimated the plasma conditions surrounding the black holes, which in our sample typically has a temperature in the range 20–100 keV and an optical depth $\tau < 4$. A more direct estimate of the electron plasma temperature and corona optical depth in AGNs will be provided in the near future by NuSTAR observations, which cover a broadband from 3–79 keV with much higher sensitivity than INTEGRAL/Swift. Indeed NuSTAR will be able to constrain all AGN spectral parameters ($\Gamma$, $E_c$, and $R$) contemporaneously with great accuracy as has recently been demonstrated (Natalucci et al. 2013).

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REFERENCES

Ajello, M., Rebusco, P., Cappelluti, N., et al. 2010, ApJ, 725, 1688
Baumgartner, W. H., Tueller, J., Markwardt, C. B., et al. 2013, ApJS, 207, 19
Beckmann, V., Barthelmy, S. D., Courvoisier, T. J.-L., et al. 2007, A&A, 475, 827
Bianchi, S., Bonilla, N. F., Guainazzi, M., Matt, G., & Ponti, G. 2009, A&A, 501, 915
Bird, A. J., Bazzano, A., Bassani, L., et al. 2010, ApJS, 186, 1
Brenneman, L. W., Madejski, G., Fuerst, F., et al. 2014, ApJ, 781, 83
Brenneman, L. W., Reynolds, C. S., Nowak, M. A., et al. 2011, ApJ, 736, 103
Comastri, A. 2004, in Multiwavelength AGN Surveys, ed. R. Mújica & R. Maiolino (Singapore: World Scientific), 323
Comastri, A., Gilli, R., & Hasinger, G. 2005, ExA, 20, 41
Dadina, M. 2008, A&A, 485, 417
de Rosa, A., Panessa, F., Bassani, L., et al. 2012, MNRAS, 420, 2087
Gandhi, P., Fabian, A. C., Suebsuwong, T., et al. 2007, MNRAS, 382, 1005
Gilli, R., Comastri, A., & Hasinger, G. 2007, A&A, 463, 79
Harrison, F. A., Craig, W. W., Christensen, F. E., et al. 2013, ApJ, 770, 103
Malizia, A., Stephen, J. B., Bassani, L., et al. 2009, MNRAS, 399, 1293
Maraschi, L., & Haardt, F. 1997, in ASP Conf. Ser. 121, IAU Colloq. 163, Accretion Phenomena and Related Outflows, ed. D. T. Wickramasinghe, G. V. Bicknell, & L. Ferrari (San Francisco, CA: ASP), 101
Matt, G. 2001, in AIP Conf. Proc. 599, X-Ray Astronomy: Stellar Endpoints, AGN, and the Diffuse X-Ray Background, ed. N. E. White, G. Malaguti, & G. G. C. Palumbo (Melville, NY: AIP), 209
Molina, M., Bassani, L., Malizia, A., et al. 2009, MNRAS, 399, 1293
Molina, M., Bassani, L., Malizia, A., et al. 2013, MNRAS, 433, 1687
Natalucci, L., Tomsick, J. A., Bazzano, A., et al. 2013, ApJ, 780, 63
Panessa, F., de Rosa, A., Bassani, L., et al. 2011, MNRAS, 417, 2426
Patrick, A. R., Reeves, J. N., Lobban, A. P., Porquet, D., & Markowitz, A. G. 2011, MNRAS, 416, 2725
Petrucci, P. O., Haardt, F., Maraschi, L., et al. 2001, ApJ, 556, 716
Tazaki, F., Ueda, Y., Ishino, Y., et al. 2010, ApJ, 721, 1340
Turner, M. J. L., Abbey, A., Arnaud, M., et al. 2001, A&A, 365, L27
Zdziarski, A. A. 1998, MNRAS, 296, L51