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High-z radio-loud QSOs observed with INTEGRAL

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We present the study of a sample 5 of "high-z" radio-loud QSOs (from z=0.1 to z=3.668) observed with INTEGRAL and XMM-Newton. The broadband coverage (0.2–100 keV) allowed us to investigate in depth the intrinsic continuum together with the absorption/emission spectral features in the soft X-ray energy range. All but one (4C04.42) sources show evidence of spectral flattening below 2–3 keV (observer frame). In the past this behaviour has been attributed either to cold/ionized absorption at the redshift of the source or to intrinsic break of the continuum. We report here, for our sample, the distribution of the absorption column density N_H and that of the intrinsic photon index. This study shows evidence that the hard-X ray selection favours "flat" sources and is able to unveils heavily absorbed objects. 4C04.42 and IGR J22517+2218 are peculiar sources among the sample: 4C04.42 shows possible evidence of bulk Compton component in the soft X-ray energy range, while IGR J22517+2218 is the farthermost QSO detected so far by INTEGRAL and represents a shining lighthouse at the edge of our Universe. For both objects a detailed spectral analysis is presented and the not-simultaneous Spectral Energy Distribution of the sources from radio to gamma ray frequencies is studied in detail.

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1. Introduction

Blazars are the most powerful objects in the observable Universe, they emit from radio frequencies up to the extreme gamma-rays. In the X-ray energy range, harder spectra are associated with the highest luminosity objects [13], and Flat Spectrum Radio Quasars (FSRQ) are the most luminous class of Blazars. The Spectral Energy Distribution (SED) of FSRQ exhibits two main peaks (one between the IR and soft X-rays and the other in the gamma-rays), disclosing the presence of two main components: it is widely believed that the low energy one is due to the Synchrotron radiation of relativistic electrons in a jet, while the high energy one is due to Inverse Compton scattering (IC) of the same electrons with a photon field [14]. It is also believed that in FSRQ the IC is due to Compton scattering of photons external to the jet (external Compton radiation EC), probably produced in the accretion disk and reprocessed by the Broad Line Region (BLR) and/or the dusty torus [7, 28]. Other competitive processes, like the IC from photons produced by Synchrotron (Synchrotron Self-Compton radiation, SSC) can contribute to the high energy component [18]. The investigation of these extreme objects in the X-ray band is important mainly because they emit most of their bolometric luminosity in this energy range [8]. Observations have demonstrated that radio-loud QSOs are more powerful X-ray emitters than radio-quiet counterparts or RQQs [22] and, therefore, more easily observable. Various authors [24, 23] have demonstrated that radio-loud QSOs exhibit a flatter intrinsic spectral shape ($\Gamma \sim$1.6) than RQQs ($\Gamma \sim$1.9); this harder X-ray emission is thought to be Synchrotron or IC emission from the relativistic radio jet, rather than from the accretion disk.

A deficit of photons in the soft X-ray band (E$<$ 2 keV observer frame) of several high and low-z QSOs has been observed in the past by *ASCA* [9, 11], and recently confirmed through *XMM-Newton*, *Chandra* and *Swift* observations [1, 27, 26]. The origin of this feature is not yet clear. Possible hypotheses are an intrinsic cold/ionized absorption or an intrinsic break of the continuum. When associated with absorption a clear trend of N_H vs z has been measured, indicating a cosmic evolution effect, which seems to be strongest at redshifts around 2 [27]. However, excess emission at similar low energies has also been observed, but only in a few sources [16, 25]. The origin of this behaviour is still unclear, even if several scenarios have been proposed and explored, like Bulk Comptonization [3], increasing contribution of the SSC component, [16], and reflection from the accretion disk [25]. So far these two spectral features (excess or deficit of soft X-ray photons), have been interpreted as due to different emission processes. However, very recently, [3] modeled the soft X-ray flattening observed in the quasar BG B1428-4217, via bulk Comptonization process. Clearly more sources need to be observed in order to improve the statistics.

Here we present a broadband analysis of a sample of 5 QSOs detected by *INTEGRAL* above 10 keV. The data below 10 keV are collected through *XMM-Newton* and *Swift* observations. The sources are the highest-z objects belonging to the 3rd IBIS/ISGRI catalogue [2]. The general properties of the sample and a spectral analysis of each single source are presented. Among the QSOs in the sample 4C04.42 and IGR J22517+2218 are peculiar: 4C04.42 [5] shows possible evidence of bulk Compton motion, while IGR J22517+2218 [1] is the most distant object observed so far by *INTEGRAL*, hence a source with a huge amount of luminosity emitted in hard X-rays. These objects are discussed here in detail[1].

[1]Throughout this paper we adopt a ΛCDM cosmology with Ω_m = 0.27, Ω_Λ= 0.73 and H_0 = 71 km s^{-1} Mpc^{-1}.

Table 1: High-z radio-loud QSOs in the 3rd INTEGRAL catalogue

Name	R.A.	Dec.	z	$^{1}N_H^{gal}$	$^{2}t_{exp}$	ref
PKS 1830-211	10 33 39.89	-21 03 39.8	2.507	0.26	2000	[6, 12]
Swift J1656.3-3302	16 56 16.56	33 02 09.3	2.4	0.22	2000	[20]
IGR J22517+2218	22 51 53.50	+22 17 37.3	3.668	0.05	262.5	[1, 17]
QSO B0836+710	08 41 24.37	+70 53 42.2	2.172	0.03	768	-
4C 04.42	12 22 22.55	+04 13 15.8	0.965	0.017	1798	[5]

[1] Galactic hydrogen column density in units of 10^{22}cm^{-2}. [2] Exposure time INTEGRAL/IBIS in units of ks.

2. High-z QSOs in the 3rd INTEGRAL survey

We describe here the broadband (0.2–100 keV) analysis of a sample of 5 objects that are representative of the "high z" QSOs belonging all but one (IGR J22517+2218), to the third IBIS/ISGRI X-ray Survey Catalogue [2]. The data below 10 keV have been collected through *XMM-Newton* and *Swift* observations. These objects, as well as the log of the available observations, are listed in Table 1. The observed flux in the sample ranges between (0.8–2)$\times 10^{-11}$erg cm^{-2}s^{-1} (1–3 mCrab) in 20–40 keV, and between (1–4)$\times 10^{-11}$erg cm^{-2}s^{-1} (1–4 mCrab) in 40–100 keV. As far as it concerns their distance, the selected objects cover a redshift range of 0.965$\leq z \leq$3.668. All but one (4C04.42) sources were well fitted, in 0.2–100 keV energy range, with an absorbed power-law model. Results of this fit are shown in Table 2, for all sources galactic absorption is taken into account. The distribution of the hydrogen column density (rest frame) of the cold absorber as obtained from the broadband analysis, is shown in the left panel in Figure 1. The distribution of N_H seems to be asymmetric, with a peak located at about log N_H=23, and a tail extending until log N_H=20. It is worth noting that the statistical significance of this result is strongly affected by the small number of objects in our sample.

In order to perform a direct comparison of our results with those obtained for a larger sample of QSOs observed in 0.3–10 keV with *XMM-Newton* [22], we reanalyzed the sample in the spectral range 0.2–10 keV. In the right panel in Figure 2 we show the comparison between the distributions of N_H for the two samples. A quick look to this figure reveals that the location of the peaks of the two distributions are in good agreement (log N_H^{peak}=22). Looking at the distributions obtained through a 2–10 keV energy band data analysis, we note that sources with absorbing column density log $N_H \geq 23$ are missing. This evidence is expected in view of the fact that in the soft X-ray energy range these sources are almost completely obscured. On the other hand, by comparing the distributions of N_H as obtained through spectral analysis in 0.2–100 keV and 0.2–10 keV, we note that a tail towards the high values of column densities appears. This strongly suggests that observations above 10 keV represent a strong tool to make an unbiased selection of heavily absorbed objects. In Figure 2 we show the distribution of the photon indices (Γ) for all the sources so far investigated, as obtained by performing the fit in the spectral range 0.2–100 keV. The mean value is $\Gamma = 1.3 \pm 0.1$. This value results to be flatter than that found by Page et al. (2005) analyzing a sample of radio-loud objects in 0.3–10 keV energy band ($\Gamma = 1.55 \pm 0.04$). The difference could be due to the hard X-ray selection of our *INTEGRAL* sample, that is clearly biased towards the

Table 2: High-z INTEGRAL QSOs: best fit model parameters

Name	$^1F_{obs}^{2-10keV}$	$^1F_{obs}^{20-100keV}$	^2C	^3N_H	Γ	χ^2_ν/dof
XMM + INTEGRAL						
QSO B0836+710	4.0	17.7	0.28±0.03	0.07 ± 0.02	1.358 ± 0.005	1.026/2423
PKS 1830-211	1.5	12.2	0.36±0.03	1.80 ± 0.10	1.11 ± 0.02	1.11/1013
Swift/XRT + INTEGRAL						
Swift J1656.3-3302	0.5	2.0	$1.9^{+1.7}_{-0.9}$	$7.9^{+5.1}_{-3.8}$	$1.66^{+0.22}_{-0.20}$	1.027/42
IGR J22517+2218	0.2	3.5	$7.1^{+6.7}_{-3.4}$	$3.6^{+3.3}_{-2.2}$	$1.66^{+0.21}_{-0.19}$	0.845/49

[1] Observed flux in units of 10^{-11}erg cm^{-2} s^{-1}. [2]IBIS/EPIC-MOS and IBIS/XRT cross calibration constant.
[3] Hydrogen column density in units of 10^{22} cm^{-2}.

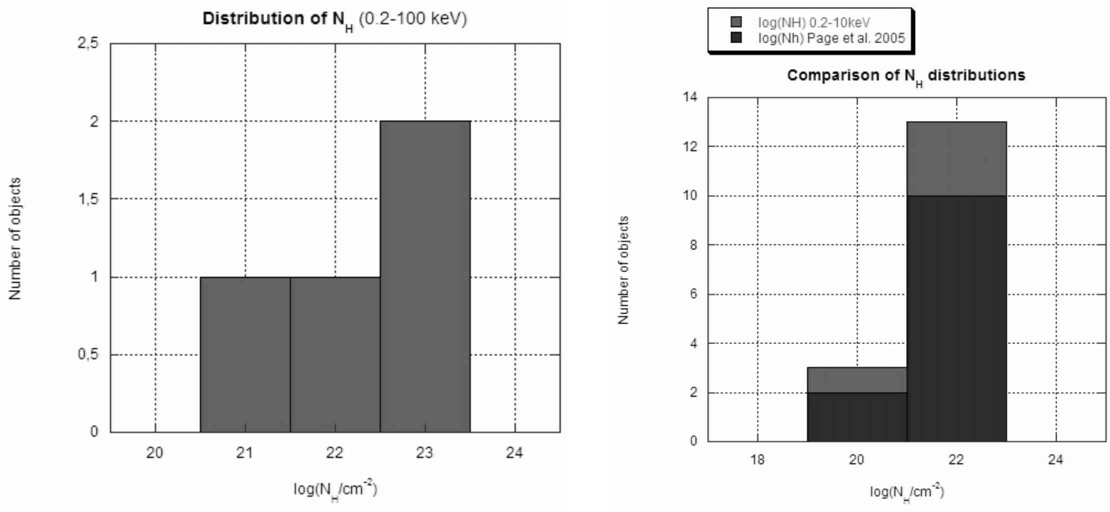

Figure 1: Distributions of the hydrogen column densities for the absorber associated with the quasars (at the quasar redshifts) in the sample. In the left panel are shown the results obtained through a broadband analysis (0.2–100 keV), while in the right panel a comparison between the distribution obtained for our sample analyzed in 0.2–10 keV and that obtained for a larger sample of QSOs observed with *XMM-Newton*[22].

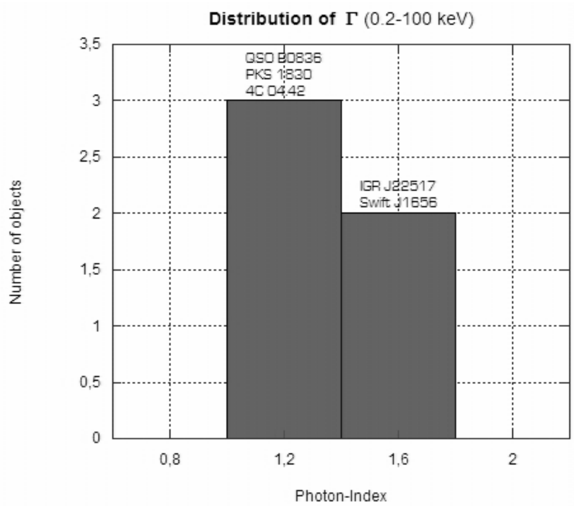

Figure 2: Distribution of the photon indices in the sample.

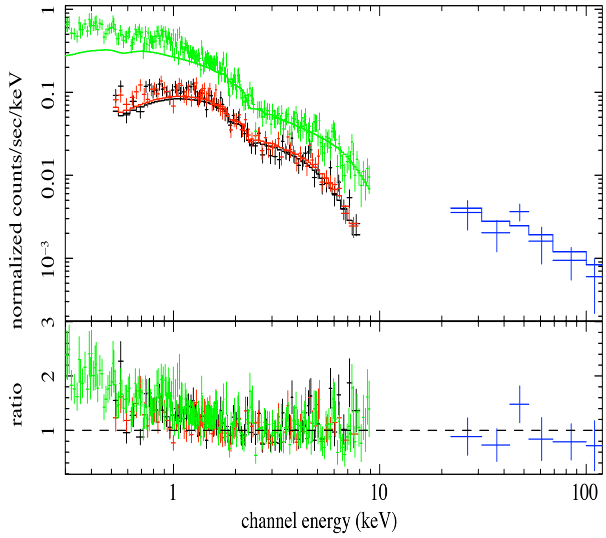

Figure 3: 4C04.42. Continuum power-law fit to the energy band above 2 keV (observer frame) extrapolated over the low energy range. Green curve: pn data, black and red curves: MOS1, MOS2 data.

flatter values of the photon index.

3. The FSRQ 4C04.42

4C04.42 was detected above 20 keV by *INTEGRAL* [2] with a flux of $(7.6\pm1.5)\times10^{-12}$ erg cm^{-2} s^{-1} and $(18.8\pm2.8)\times10^{-12}$ erg cm^{-2} s^{-1} in 20–40 keV and 40–100 keV bands respectively. It was later observed by *XMM-Newton* for $\sim$10 ks. The broadband analysis of 4C04.42 in 0.2–100 keV, through non simultaneous *XMM-Newton* and *INTEGRAL* data provide strong evidence for soft excess emission below 2 keV (see Figure 3). This excess is well reproduced either with a thermal component with temperature kT$\sim$ 0.2 keV or with a broken power–law with $\Delta\Gamma$=0.4 and the break energy E_{br}= 2 keV.

In Figure 4 we show the SED of 4C04.42 where non simultaneous data across the electromagnetic spectrum have been taken from NED[2]. In FSRQ the two peaked SED is interpreted in the Synchrotron External Compton framework [14]: the low frequency peak in the IR or FIR is created through the Synchrotron radiation of relativistic electrons moving in a blob, of dimension R, originating in the jet and having a magnetic field of few Gauss. The high frequency peak in the hard-X and gamma-rays is believed to be the effect of IC scattering of the same electrons population on a photon field that can be caused (1) by the Synchrotron radiation (SSC) and/or (2) by thermal emission from the accretion disk, BLR and/or dusty torus (EC). Due to the high density of the external photon field, the EC in FSRQ dominates over the SSC. The secondary effect on the SED derived from EC in the molecular torus, distant on the scale of pc from the central black hole, is not considered here.

A model that well reproduce the SED[3] is also included in Figure 4. The simplest hypothesis is that the emitting region is a blob of radius R moving with a bulk velocity of βc (where β =

[2]NRAO Extragalactic Database; http://nedwww.ipac.caltech.edu/index.html

[3]SSC code from http://www.asdc.asi.it/ssc_at/. The model was used in e.g. [21] and [6]

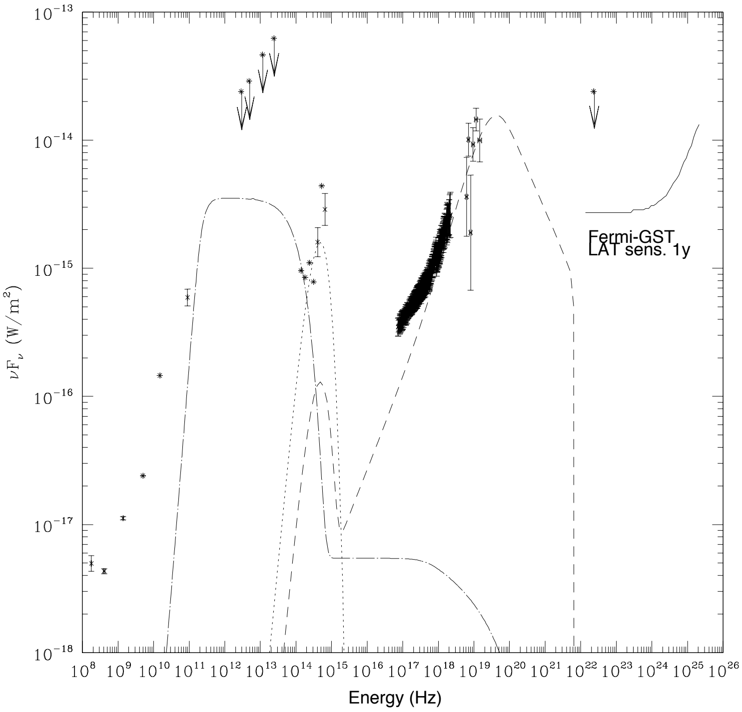

Figure 4: 4C04.42. Spectral Energy Distribution from radio up to soft gamma-ray frequencies. Data are from literature taken by NED. The solid line represents the sensitivity curve for 1 year observation with Fermi-LAT.

$\sqrt{\Gamma^2-1}/\Gamma$, and Γ is the Lorentz factor), in a magnetic field with intensity of 2 Gauss. We assume an observing angle of $\theta \sim 1/\Gamma$ implying a Doppler factor $\delta = \Gamma$. The SSC+EC components are plotted separately in Figure 4 with long dashed-dotted and dashed lines respectively. The disk contribution (dotted line) is shown as a thermal component with temperature of $kT_{BB,z}$ =1 eV in the quasar rest frame. No other additional component, such as reflection from the disk, has been included in the model. In the figure is also plotted the sensitivity curve for 1 year observation with the Fermi/LAT.

The dimension of the emitting blob, the magnetic field, the electron energy distribution, and the Lorentz factor are the only parameters required to evaluate the SSC component in the SED. We assume that the electrons in the blob are well described by a power-law, $N(\gamma)$=N γ^{-p} cm^{-3}, in the range γ_{min} and γ_{max}, and we do not take into account radiative cooling of the electrons. We stress that our model for the whole SED is not a true "fit". In view of the not simultaneous data set, we just attempt to extract some physical parameters from the data, with the main goal to obtain average properties of the source. In particular the EC component did allow us to constrain γ_{max}, and p. The EC component due to the BLR photon field is determined by the BLR energy density U_{BLR}. We fixed the disk luminosity at the level of the optical-UV emission (at 10^{15} Hz in the quasar rest frame) observed in the source SED. The BLR luminosity is estimated assuming that the emitting region reprocesses a fraction of the disk luminosity that is ∼0.1 [19]. The energy density in the observer frame is given by U^{oss}_{BLR}=L_{BLR}/$4\pi c R^2_{BLR}$, so that the contribution of the IC emission to the

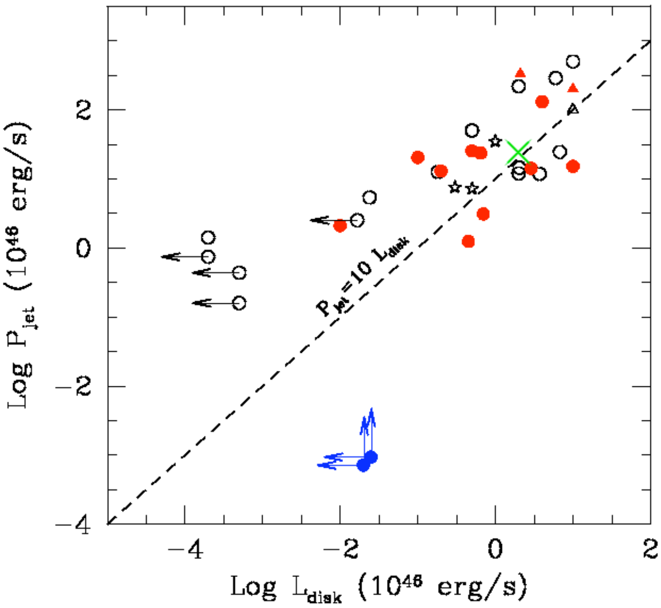

Figure 5: Total jet power vs disk luminosity for different samples of blazars studied in [19, 25, 17]. The green cross represents the location of FSRQ 4C04.42.

SED is P_{EC}=4/3$\sigma_T c\delta^4 \int_{\gamma_{min}}^{\gamma_{max}} N(\gamma)\gamma^2 U_{BLR}^{oss}\Gamma^2 d\gamma$= 8×10^{-2} $R_{BLR,17}^{-2}$ erg cm^{-3} s^{-1}, where $R_{BLR,17}$ is the BLR extension in units of 10^{17} cm. R_{BLR} is measured in very few AGN through reverberation mapping [15], where a relation between R_{BLR} and $\lambda L_\lambda(5100\ \dot{A})$ is assumed. Taking $\lambda L_\lambda(5100\ \dot{A})$ from the SED, we have R_{BLR}=5×10^{17} cm. In the emitting volume given by V=4/3πR^3, we would then expect L_{EC}=3×10^{47} erg s^{-1}, in agreement with the value reported in the SED.
Figure 4 clearly shows evidence that the SSC+EC model does not well fit the whole SED. In particular an excess, of about a factor of three with respect to the EC component, is visible around 2 keV. This soft X-ray excess could be due to bulk Compton of a "cold" shell of plasma moving in the jet and interacting with the external BLR photon field [3]. The luminosities of the Bulk and External Compton components, L_{BC} and L_{EC}, are determined by the relative normalization of the number densities of the cold and relativistic electrons. The number of cold electrons is usually difficult to verify since low energy electrons emit synchrotron light in the self-absorbed range, and SSC radiation at low frequencies, where the flux is dominated by the Synchrotron emission of electrons of higher energies. The only way to observe the bulk Compton component in the SED is when it dominates the non thermal continuum in the soft X-ray energy range, and this will happen when the competitive processes, like SSC, are negligible in this band. However, here we do not try to fit this excess with a bulk Compton component, we just stress that with Γ=20, as assumed in our model, we expect to detect the peak of such component at the frequency of $\nu_{BC} = \Gamma^2 \nu_{BLR}/(1+z) \sim$

1 keV, i.e. where the excess is indeed observed. In addition, if the excess is interpreted as due to bulk motion then L_{BC}=4/3σ_Tcδ^4 $U^{oss}_{BLR}\Gamma^2 N_c \sim 10^{46} N_c/N$, where N_c is the number of cold electrons in the blob. With the value we obtained with our broadband analysis, $L_{BC} \sim 10^{45}$ erg s^{-1}, we estimate the ratio N_c/N to be $\sim$ 0.1. Very recently the bulk Compton process has been proposed as a means to explain the steepening of the spectrum in the case of quasars PKS 1510-089 at z=0.361 [16], 0723-679 at z=0.847, 1136-135 at z=0.554, and 1150-497 at z=0.334 [25]. The bulk Compton process has been also proposed to explain the observed flattening in the powerful blazar BG B1428+4217, at z=4.72 [3]. In this source the soft X-ray behaviour was previously attributed to warm absorption intrinsic to the source [9, 10, 27]. We also stress here that flattening of the spectral emission has been observed in high-z quasars up to z=4.4, while the softening has been observed in very few sources, and all are at redshifts below 1.

The comparison between the power carried by the jet P_{jet}, and the disk luminosity L_{disk} gives information about important physical quantities Under the assumption of one proton per emitting electron in the jet composition, the jet kinetic power is $P_{jet}=\pi R^2 \beta \Gamma^2 cU$, where $U=U_B+U_e+U_p$ is the total energy in the jet rest frame due to magnetic field, electron and protons. For 4C04.42, using the model we employed to reproduce the SED and γ_{min}=1, we obtain $L_{disk}/P_{jet} \sim$0.1 which is in very good agreement with the other cases where this ratio was evaluated with good accuracy [19, 25]. In the plane L_{disk} *vs* P_{jet} (see Figure 5), 4C04.42 lies in the region of high-luminosity blazars, following the trend observed in other similar sources. This, in turn, implies that a large fraction of the accretion power is converted in bulk kinetic energy of the jet [19, 4].

4. IGR J22517-2218: a gamma-ray lighthouse in the Universe

IGR J22517+2218 was detected by IBIS with a significance of $\sim 7\sigma$ at a position corresponding to R.A.(2000)=22h51m42.72s and Dec(2000)=+22° 17'56.4" and with a positional uncertainty of 4.5' (90% confidence level). Follow up observations with the Swift/XRT telescope confirmed the association of IGR J22517+2218 with the high redshift QSO MG3 J225155+2217 at z=3.668. A simple power law model well fit the IBIS data (χ^2=6.5 for 8 d.o.f.) with a photon index Γ=1.4$\pm$0.6 combined to an observed 20–100 keV (100-500 keV in the source rest frame) flux of 4×10^{-11} erg cm^{-2} s^{-1}.

A power law also provides a good fit to the Swift/XRT data (three available observations) and a trend of decreasing flux from 4.4 to 2.7 $\times$ 10^{-12} erg cm^{-2}s^{-1} becomes evident over a 6 day period. Since the *INTEGRAL* detection is over a few revolutions, i.e provides an average flux, to improve the statistics the two most statistically significant XRT spectra have been combined. This average spectrum fitted with a power-law has an acceptable χ^2/dof =46.9/53 and a flat photon index (Γ=1.31$\pm$0.09). However, residuals to this model show some curvature possibly due to intrinsic absorption in the source rest frame (see left panel in Figure 6). Addition of this extra component provides a fit improvement which is significant at the 99.98 % confidence level according to the F test, a more typical radio-loud AGN spectrum ($\Gamma \sim$1.6) and a mild column density (N_H=3$\pm$2 $\times$ 10^{22} cm^{-2}). However, a broken power law also provides an equally significant improvement in the fit, with a break energy at 1.55$\pm$ 0.15 keV and a spectral flattening of $\Delta\Gamma$= 0.5 (Γ_1=0.7$\pm$0.3 and Γ_2=1.2$\pm$0.4). While a perfect match in spectral shape with $\Gamma \sim$1.6 is found, the XRT data fall short

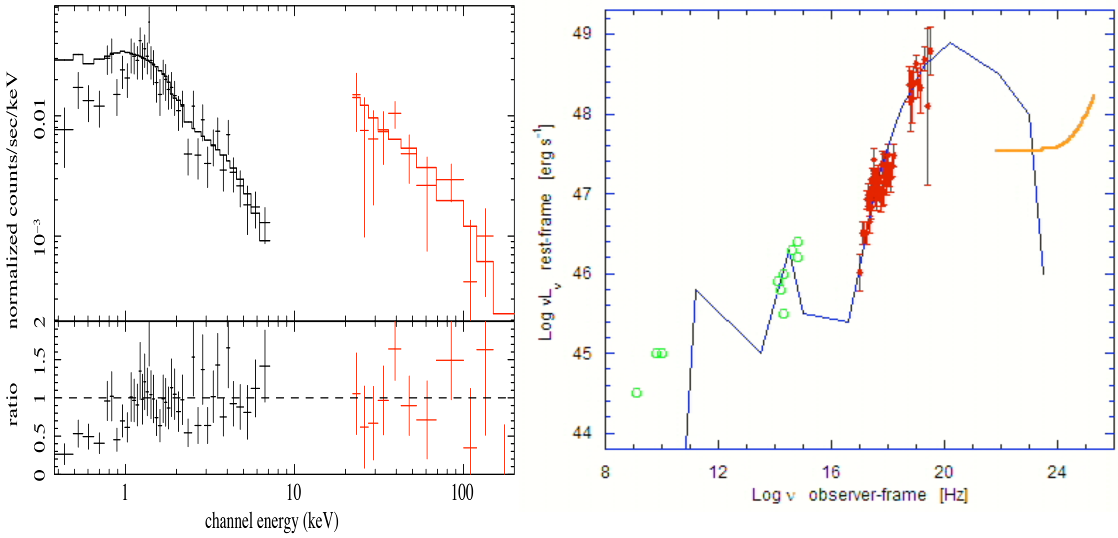

Figure 6: IGR J22517+2218. Left panel: Continuum power-law fit to the energy band above 2 keV (observer frame) extrapolated over the low energy range. Right: Not simultaneous SED from radio frequencies up to gamma-rays. The sensitivity curve for 1 year observation with Fermi-LAT is also shown. The model is that proposed in [17].

of the *INTEGRAL* detection by a factor in the range 3-7 (see Table 2), implying again variability in the source flux as also evident in the sequence of XRT observations.

The rest frame luminosities are of 0.3×10^{48} erg s^{-1} in the X-ray (2–10 keV) band, 2×10^{48} erg s^{-1} at hard X-rays (20–100 keV) and 5×10^{48} erg s^{-1} in the soft gamma-ray (100–500 KeV) interval, i.e. MG3 J225155+2217 is an X/gamma-ray lighthouse shining from the edge of our Universe.

IGR J2251+2218 is a blazar/FSRQ. The not-simultaneous SED from radio frequencies to gamma-rays is shown in the right panel in Figure 6, the model is that described in [17]. This SED is "unusual" among such type of blazars as it is compatible with having the synchrotron peak in the X/gamma-ray band (i.e. much higher than generally observed) or alternatively with the Compton peak in the MeV range (i.e. lower than typically measured). Indeed, the X-ray to radio flux ratio is $\sim$ 1000 (or $\alpha_{xr} < 0.75$), similar to high energy peaked blazars, i.e. those with the synchrotron peak in the X-ray band; this is further supported by the observed shape of the infrared to optical continuum which is at odds with the location of the synchrotron peak at infrared frequencies as generally observed in FSRQ. A detailed model of the SED [17] has shown that the hard X-ray *INTEGRAL* data well define the decreasing part of the EC component. This model has also defined with a good accuracy the location of the EC peak energy, that is around 500 keV observer frame. Either way, MG3 J225155+2217 is quite atypical for its class and an extreme object in the blazar population; this makes it an interesting laboratory in where to test current blazars theories and so an object worth following up at all wavebands.

5. Conclusions

We have presented the broadband spectral study of a small sample of 5 radio-loud QSOs observed whit *INTEGRAL*, *XMM-Newton* and *Swift*. Our main results are:

- All sources but 4C04.42 are characterized by a 0.2–100 keV spectrum that is best reproduced with an absorbed power–law model. The distribution of N_H is asymmetric, with a peak located at about log N_H=23, and a tail extending to log N_H=20. A comparison between the distributions of the column density obtained through the analysis performed in 0.2–10 keV and 0.2–100 keV confirms that the observations above 10 keV represent a strong tool to select heavily obscured objects.

- The mean value of the photon index is lower than that obtained analyzing a sample of QSOs observed in 0.2–10 keV with *XMM-Newton*. This effect is probably due to the hard X-ray selection that favours the sources with a flatter photon index.

- The broadband analysis of one source of the sample, the FSRQ 4C04.42, shows the presence of a soft excess in the soft X-ray energy range. This excess, as well as the flat spectral shape in hard X -rays, strongly suggests the presence of a population of cold electrons able to produce a bulk Compton feature at $\sim$ 1 keV through IC with the photon field of the BLR. In addition the ratio L_{disk}/P_{jet} $\sim$0.1 between the disk luminosity and the power carried by the jet, implies that a large fraction of the accretion power is converted in bulk kinetic energy of the jet.

- Among the sample, IGR J22517+2218 is the most distant object so far detected by *INTEGRAL* and the second most distant blazar ever observed above 20 keV. The study of its not-simultaneous SED show evidence that the IC component is dominant with respect to that due to Synchrotron. Observation with Fermi-LAT will be crucial to investigate in depth the emission of this lighthouse in our Universe.

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