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# Suzaku hard X-ray view of Seyfert galaxies

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Thanks to well-calibrated instruments and a low background level, Suzaku could measure the broad-band X-ray spectra more precisely than ever, and also trace the subday time variability up to 40 keV. Therefore we can decompose the spectral components by performing a broad-band fitting and by utilizing a different time scale of each component, and constrain the physical structure of the nuclear region. Here we report on systematic studies of nearby 28 Seyfert galaxies with Suzaku, utilizing a recently improved background model. The overall spectrum is well described by the power-law model with partial covering absorption, together with Fe-K line structures and reflection hump above 10 keV. The reflection fraction is sometimes different from those in the previous measurements, possibly due to different time scales between direct nuclear component and reflection component. Flux-flux correlation or energy-dependent rms could be traced up to 40 keV for some AGNs, thanks to their subday time variability. These indicate that two-component spectral models are generally accepted, and the less variable fraction inferred from the timing analysis is almost consistent with that obtained by the spectral fitting. Therefore, Suzaku is very powerful to decompose the complex spectral features of Seyfert galaxies. Accordingly, we can constrain the physical properties of reflection and absorption material better than ever. The center energy and width of the Fe-K line is strongly constrained to be $6.395\pm0.005$ keV and $<2500$ km/s. Fe abundance of the reflector is also well constrained to be 0.6–1.2 solar, thanks to precise measurements of both Fe-K line and reflection continuum. These findings support that the reflector is $> 0.1$ pc away from the nucleus. The large equivalent width and (back-scatter) Compton shoulder in the Fe-K line for Compton-thin AGNs indicate various types of material with different Compton-thickness around the nucleus. In some case the reflection fraction is small regardless of large absorption column, indicating that the absorber is inhomogeneous rather than a regular and uniform torus.

*7th INTEGRAL Workshop*
*September 8-11 2008*
*Copenhagen, Denmark*

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[†]We thank to the Suzaku team for hardware and software development, calibration, and operation.

 

PoS(Integral08)051

## 1. Introduction

Seyfert galaxies show a bright X-ray emission from the nuclear region, but the X-ray spectra have been found to be very complex. The direct nuclear emission is thought to be a power-law model with a high energy cut-off around several 100 keV. However, the surrounding medium around the supermassive black hole creates complex spectral structures. Material toward the line of sight causes a soft X-ray absorption. Recent X-ray observations have revealed that the absorption is not simple but partial covering with ionization. Highly ionized thin material is also found as Fe-K resonance absorption lines. Part of nuclear emission is reflected by the material such as accretion disk or molecular torus and it appears as reflection hump peaking around 40 keV with fluorescent elemental lines.

Then, study of X-ray spectra of Seyfert galaxies is very important to probe the surrounding material around the supermassive black hole by using the above spectral features. These material are fuel of black holes and thus valuable to investigate the evolution of black hole. It is interesting how the geometry a so-called molecular torus is, how far away the torus exists from the nucleus, how about the disk structure. Also the spectral shape of the nuclear direct emission is interesting, because we can obtain the information about the physical properties of AGN central engine; temperature, density, energy distribution of hot corona. These are important to understand the geometry and physical state of the hot corona.

However, due to the complex spectral structures, the spectral fitting is very difficult and we cannot avoid the modeling ambiguity such as parameter coupling. Wide-band X-ray spectroscopy from sub-keV to several 100 keV is essential to resolve this issue. BeppoSAX/PDS gave many opportunities of such studies for Seyfert galaxies. Risaliti (2002)[17] and Malizia et al. (2003)[12] reported that the photon index of Seyfert 2 galaxies tend to be smaller than that of Seyfert 1 ones. However, the different tendency was obtained by Deluit and Courvoisier (2003)[2]. Deluit and Courvoisier (2003) claimed that the cut-off energy of Seyfert 2 galaxies is lower than that of Seyfert 1 galaxies. Risaliti (2002)[17] summarized the photon index, reflection fraction, and cut-off energy for Seyfert 2 galaxies, but they are less constrained than those of Seyfert 1 galaxies.

The Suzaku XIS/HXD combination (Mitsuda et al. 2007, Koyama et al. 2007, Takahashi et al. 2007, Kokubun et al. 2007)[14, 9, 20, 8] is very powerful to study the spectral structures of Seyfert galaxies. They cover a wide X-ray band in 0.4–500 keV simultaneously, and thus we can constrain the spectral shape accurately. The well-calibrated XIS and low background of both instruments give us a spectrum with high quality above 6 keV, and we can measure the Fe-K structures with high accuracy of energy determination and good constraint of the underlying continuum. The low-background HXD-PIN (figure 1) without rocking motion enables us to perform the short-term timing analysis even above 10 keV, which gives us another tool of spectral decomposition. The HXD-GSO gives us important information of the high energy part in 50–200 keV. Here we report the Suzaku hard X-ray view of Seyfert galaxies, focusing on the spectral structure above 2 keV, referring to the publications, together with our systematic analysis of the Suzaku archival data of 28 Seyfert galaxies. Here we utilized a recently developed HXD-PIN/GSO background model (Fukazawa et al. 2009)[4]. Table 1 summarizes the analyzed sample of Seyfert galaxies. All objects are detected up to several tens of keV with HXD-PIN, and thus the flux above 10 keV is higher than 0.5 mCrab. 18 of them are Seyfert 2 galaxies, and consequently the spectra are often



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heavily absorbed in the soft X-ray band.

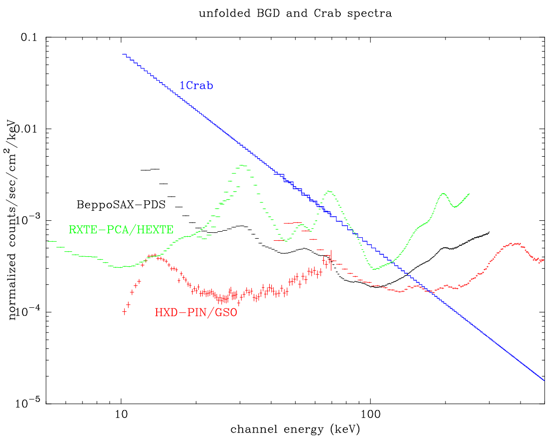


**Figure 1:** Comparison of the background level between the Suzaku-HXD and others. The background count rate is normalized by the effective area.

**Table 1:** Sample of Seyfert galaxies.

| | | | |
|---|---|---|---|
| 3C120 | CENTAURUS A | CIRCINUS GALAXY | IGRJ16318-4848 |
| IRAS19254-7245 | M81 | M106 | MCG-5-23-16 |
| MCG-6-30-15 | MRK3 | MRK79 | MRK273 |
| MRK335 | MRK509 | NGC1068 | NGC2110 |
| NGC3516 | NGC3783 | NGC4051 | NGC4388 |
| NGC4945 | NGC4992 | NGC5728 | PKS2356-61 |
| SWIFTJ0138.6-4001 | SWIFTJ0505.7-2348 | SWIFTJ0601.9-8636 | SWIFTJ1628.1+5145 |

## 2. Wide-band High Signal-to-Noise Spectra

Suzaku observed several bright Seyfert galaxies, providing high signal-to-noise spectra which enable us to determine the spectral shape more accurately than past observations. An accurate determination of the underling continuum shape is very important to study the broad Fe-K line. The disk-line structure and reflection fraction were well constrained for MCG-6-30-15 (Miniutti et al. 2007)[13], MCG-5-23-16 (Reeves et al. 2007)[16], NGC 3516 (Markowitz et al. 2008)[11], and then both the broad and narrow Fe K$\alpha$ line as well as the reflection hump are unambiguously detected. Well-calibrated XIS energy scale could constrain the ionization level of fluorescent Fe-K lines to be $<Fe^{+10}$; NGC 2992 (Yaqoob et al. 2007)[22], Cen A (Markowitz et al. 2007)[10], NGC 4388 (Shirai et al. 2008)[19], and Mrk 3 (Awaki et al. 2008)[1].

Here we show the results of NGC 2110 (Okajima et al. 2007)[15], which was observed on Sep. 16–18, 2005, when NGC 2100 brightened up to 10–20 mCrab. The broad-band X-ray spectrum was obtained up to 200 keV, and a simple power-law with an absorption and Fe-K line does not fit the spectrum well; a residual excess around 1 keV and Fe-K edge, together with a significant deviation from the power-law above 10 keV. Such a deviation reminds us of a reflection hump. However, regardless of a large change of the continuum flux, the depth of the Fe-K edge is $\tau = 1.0 \pm 0.2$, almost similar to that in the normal state (Hayashi et al. 1996)[5]. This indicates that the edge is not due to the reflection. Then, a partial covering absorption model explains that the deep edge is due to a thick absorber and the soft residual is due to a leakage of the direct emission through a thin absorber. The best-fit spectrum is shown in figure 2. The power-law photon index becomes $1.77 \pm 0.02$ against 1.60 of the simple absorption model. Absorption is somewhat complex; full covering of $N_{\rm H} = 3.0 \times 10^{22}$ cm$^{-2}$, a partial covering of the thin absorber of $3.6 \times 10^{22}$ cm$^{-2}$ with a fraction of 0.45 and the thick absorber of $5.0 \times 10^{23}$ cm$^{-2}$ with a fraction of 0.14. The reflection is not needed with a fraction of $< 0.1$. In other AGNs, it is reported that a partial covering absorption is needed; Cen A (Markowitz et al. 2007)[10], NGC 4388 (Shirai et al. 2008)[19], and NGC 3516 (Markowitz et al. 2008)[11]. Therefore, it is suggested that the absorber or reflector consists of multi-phase structures and a simple one-zone absorption model is not accurate. Such a multi-phase absorber is also required to explain a time variability of the absorption column density for several Seyfert 2 galaxies (Elvis et al. 2004, Risaliti et al. 2005)[3, 18] with RXTE, Chandra, and XMM-Newton. The results of NGC 2110 demonstrates a Suzaku advantage of a snap-shot observation to study a spectral shape with high signal-to-noise ratio.

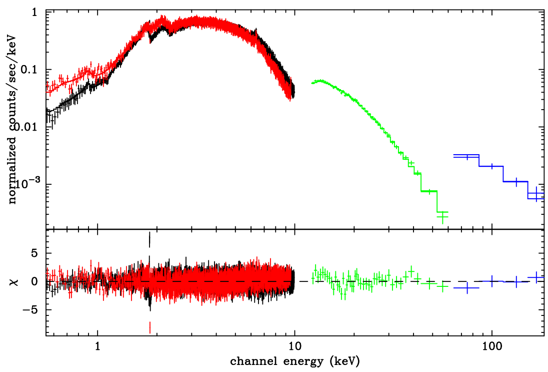


**Figure 2:** Suzaku spectrum of NGC 2110. Best-fit model is cut-off power-law with a partial covering absorption.

## 3. Spectral Decomposition

Studies of time variability of spectra is an independent tool to decompose the spectrum against the simple spectral fitting. The direct nuclear component is mostly time variable with a time scale of $\sim 1$ day for $10^7 M_\odot$ black hole mass, while the reflection component from the distant matter is less variable with a time scale of $>$1 month. Therefore difference of time scale between two components will enable us to decompose them, and wide-band X-ray study is very important to constrain the direct component below 10 keV and the reflection component above 10 keV. The HXD-PIN enables us to study the short-term variability above 10 keV for many AGNs for the first time, and thus it is very useful for this study. Such studies are successfully performed for MCG-6-

30-15 (Miniutii et al. 2007)[13], MCG-5-23-16 (Reeves et al. 2007)[16], NGC 4388 (Shirai et al. 2008)[19], NGC 4051 (Terashima et al. 2008)[21], with Suzaku.

Figure 3 shows a PIN light curve of NGC 4388, for which the intraday time variability was for the first time confirmed for this object with Suzaku. The flux correlates well between XIS and PIN energy band, indicating that the two component model is reasonable, as well as MCG-6-30-15 (Miniutti et al. 2007)[13]. Also a RMS spectrum, an energy-dependent root-mean-square of time variability, shows a small variation toward the higher energy band. This is consistent with that the constant reflection component becomes dominant in the higher energy band. The spectra in the high and low state are successfully fitted with a variable power-law component plus a constant reflection and Fe-K line. The photon index of the direct power-law component is constrained to be 1.75±0.15. The difference spectrum between the high and low state, which is likely the direct nuclear component, shows no significant Fe-K line and is well fitted with the simple power-law model with the above photon index, as shown in figure 4. Unlike Seyfert 1 galaxies for which the difference spectra have been studied with XMM-Newton, measurement of the spectral shape of the direct nuclear components is not easy for Seyfert 2 galaxies, since the unabsorbed spectral shape cannot be observed below 10 keV. Therefore, the results obtained for NGC 4388 demonstrate that Suzaku can extract the direct component as a difference spectra for Seyfert 2 galaxies.

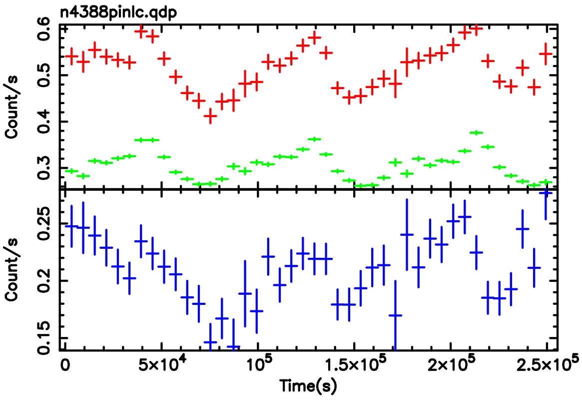


**Figure 3:** HXD-PIN light curve of NGC4388. Top panel shows a total count rate (red) and background model count rate (green), and bottom panel shows a background-subtracted count rate (blue).

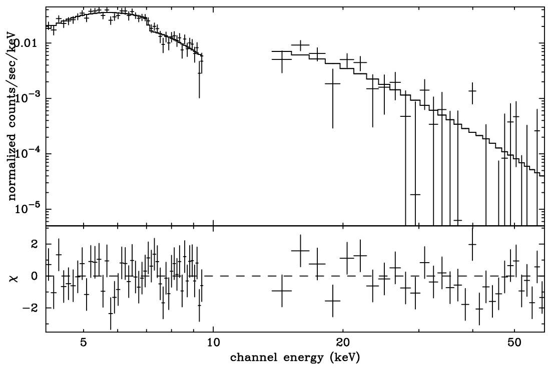


**Figure 4:** Difference spectra between the high and low state of NGC 4388. Best-fit model is a simple absorbed power-law.

Extraction of only the direct nuclear emission is important to determine the photon index of the power-law component. For Seyfert 2 galaxies, determination of the power-law photon index is somewhat difficult for spectral fitting due to complex absorption. In fact, simple spectral fitting with one-zone absorption gives a flat photon index, but measurements with studies of time variability recovers the photon index close to the canonical values; 1.2 → 1.75±0.10 (NGC 4388), 1.5 → 1.76±0.05 (NGC 3516). Even in the spectral fitting, consideration of complex absorption gave 1.6 → 1.77±0.02 for NGC 2110. Figure 5 shows a distribution of the power-law photon index of Seyfert 2 galaxies, obtained with Suzaku by studies of time variability or partial covering model. The photon index narrowly distributes in the range of 1.7–1.9, and there is no significant difference between Seyfert 1 and 2 galaxies. However, in the case of Compton-thick objects, the recovery of photon index might be incomplete. Another important is that the Fe-K narrow line often disappears in the difference spectra as well as the reflection component, indicating that the narrow Fe-K line comes from the distant matter far away from the nucleus. Spectral decomposition with time variability also opens the study of the jet emission. Kataoka et al. (2007)[7] extracted the jet steep emission with a fast variability from the disk emission with a slower variability for a broad line radio galaxy 3C120. Since jet emission from radio galaxies is not so relativistically boosted, it is often hidden by the disk emission. But it is important to probe the jet structure and understand the disk-jet connection.

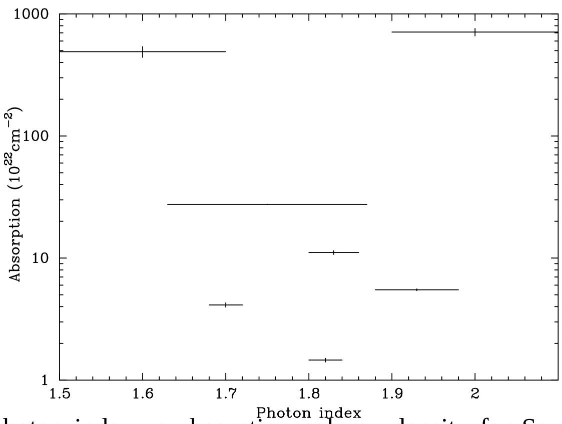


**Figure 5:** Power-law photon index vs absorption column density for Seyfert 2 galaxies observed with Suzaku.

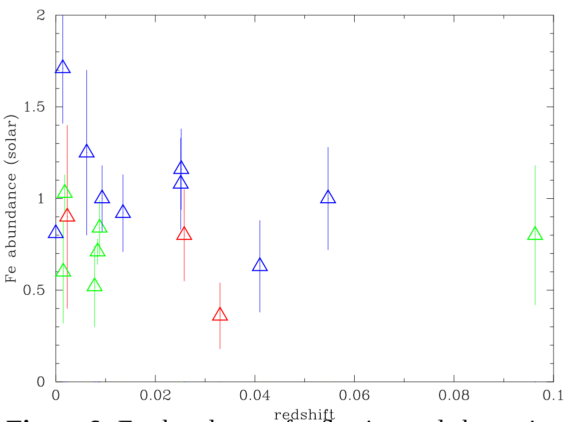


**Figure 6:** Fe abundance of reflection and absorption material, against the redshift, obtained with Suzaku. The red, greem and blue points are Seyfert 1, compton-thin Seyfert 2, compton-thick Seyfert 2, respectively.

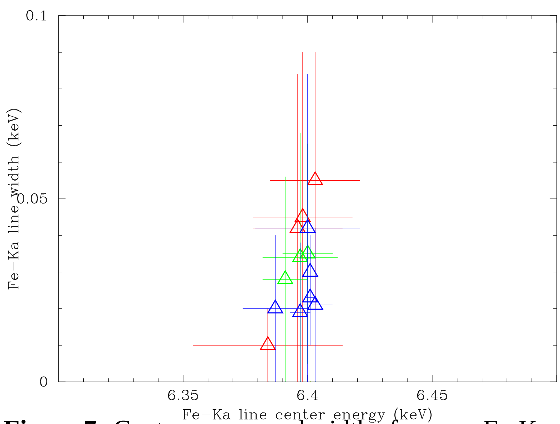


**Figure 7:** Center energy and width of narrow Fe-K$\alpha$ line, obtained with Suzaku. The colors are the same as figure 6.

## 4. Properties of reflection or absorption material

In this section, we describe the improved understanding of the reflection or absorption material obtained with Suzaku. Suzaku can constrain the Fe abundance well by using both Fe-K edge depth and reflection hump, and such a measurement was demonstrated by Reeves et al. (2007)[16]. Figure 6 shows the Fe abundances of reflection matter. For Seyfert 2 galaxies whose Fe-K edge is also due to the absorption, we assume the Fe abundance of the absorber to be the same as that of the reflector. The Fe abundance is in the range of 0.6–1.2 solar, constrained more tightly than ever, and no evidences of Fe supersolar abundance. Therefore, it is possible that the past reports of Fe supersolar abundance is due to the apparent deep edge by the multi-layer absorption, as seen for NGC 2110 or the ionized absorber. Figure 7 shows the scatter plot between the center energy and the width of the Fe-K$\alpha$ fluorescence line. These quantities are also determined better than ever, leading to the constraint of the ionization state of reflector. The center energy narrowly distributes at 6.385–6.405 keV, indicating that the Fe ionization is less than 10th. For some bright objects, Fe K$\alpha$ to K$\beta$ line intensity ratio can be measured to give a similar upper limit of ionization, as demonstrated by Yaqoob et al. (2007)[22], Awaki et al. (2008)[1], and Shirai et al. (2008)[19]. The line width is mostly less than 2500 km/s, indicating that the reflector is at $> 0.1$ pc far away from the nucleus. Apart from the narrow Fe-K$\alpha$ line, broad Fe-K$\alpha$ line is also confirmed in some objects; MCG-6-30-15, MCG-5-23-16, NGC 3516, and 3C120.

The Suzaku wide-band high sensitive observations is advantageous also for studies of Compton-thick objects. Ueda et al. (2007)[23] found that two Swift hard X-ray sources (Swift J0136.6-4001 and Swift J0601.9-9636) exhibit a Compton-thick absorption and a weak scattering component. Considering the optical non-activities of these objects, they suggest that these objects have a geometrically thick torus, by which most of scattering or reflection component are also blocked. Itoh et al. (2008)[6] indicated that a large variation amplitude of the flux and a broad-band spectral fitting requires a reflector with a small solid-angle of a few $< 10^{-2} \times 2\pi$ for NGC 4945. On the other hand, a strong reflection component is detected for Mrk 3 (Awaki et al. 2008)[1], NGC 4388 (Shirai et al. 2008)[19] and so on, and thus these objects might have a torus whose geometry is typical. Suzaku has observed many Compton-thick Seyfert 2 galaxies, based on the Swift/BAT and INTEGRAL sources. Figure 8 shows an example of their spectra, where it can be seen that the scattering or reflection component in the soft X-ray band is often weak with $< 1\%$ of the direct emission. Therefore, the geometry of the torus is indicated to be various types; geometrically thick like Swift J0136.6-4001 and Swift J0601.9-9636, geometrically thin like NGC 4945. Other cases also suggests that the scattering/reflection component varies with some delay against the direct emission and the scattering/reflection is occasionally weak when the nucleus begins the activity after quiescence. In fact, a long-term variation of the reflection fraction was observed with Suzaku and previous observations (Shirai et al. 2008)[19]. Thus, Suzaku will give us important new information on the properties of the absorber and reflector.

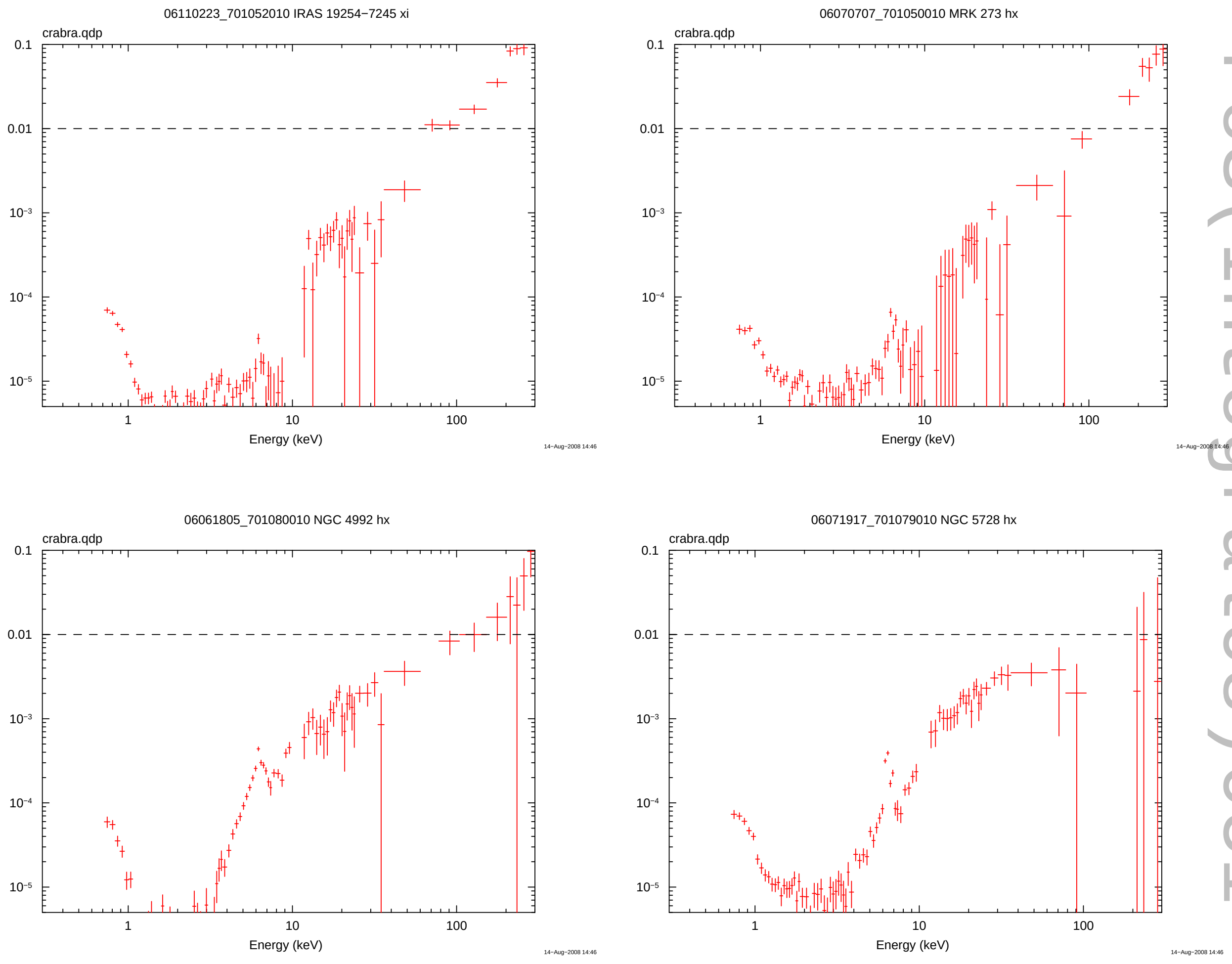


**Figure 8:** Examples of Suzaku spectra of Compton-thick Seyfert 2 galaxies as represented by the Crab ratio. Top-left, top-right, bottom-left, and bottom-right are IRAS19254-7245, Mrk273, NGC4992, and NGC5728, respectively.

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