The Nature of Stable Soft X-Ray Emissions in Several Types of Active Galactic Nuclei Observed by Suzaku

Hirofumi NODA,1 Kazuo MAKISHIMA,1,2,3 Kazuhiro NAKAZAWA,1 Hideki UCHIYAMA,1 Shin’ya YAMADA,2 and Soki SAKURAI1

1 Department of Physics, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-0033
2 Institute of Physical and Chemical Research (RIKEN), 2-1 Hirosawa, Wako-shi, Saitama 351-0198
3 Research Center for the Early Universe, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-0033

noda@juno.phys.s.u-tokyo.ac.jp

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Abstract

To constrain the origin of the soft X-ray excess phenomenon seen in many active galactic nuclei, the intensity-correlated spectral analysis, developed by Noda et al. (2011, PASJ, 63, S925) for Markarian 509, was applied to wide-band (0.5–45 keV) Suzaku data of five representative objects with a relatively weak reflection signature. They are the typical bare-nucleus type 1 Seyfert Fairall 9, the bright and typical type 1.5 Seyfert MCG –2–58–22, 3C 382, which is one of the X-ray brightest broad line radio galaxies, the typical Seyfert-like radio loud quasar 4C +74.26, and the X-ray brightest radio quiet quasar MR 2251–178. In all of them, soft X-ray intensities in energies below 3 keV were tightly correlated with that in 3–10 keV, but with significant positive offsets. These offsets, calculated in finer energy bands, define a stable soft component in 0.5–3 keV. In each object, this component successfully explained the soft excess above a power-law fit. These components were interpreted in several alternative ways, including a thermal Comptonization component that is independent of the dominant power-law emission. This interpretation, considered physically most reasonable, is discussed from a viewpoint of Multi-Zone Comptonization, which was proposed for the black hole binary Cygnus X-1 (Makishima et al. 2008, PASJ, 60, 585).

Key words: galaxies: active — galaxies: individual (Fairall 9, MCG –2–58–22, 3C 382, 4C +74.26, MR 2251–178) — galaxies: Seyfert galaxy, Radio galaxy, Radio loud quasar, Radio quiet quasar — X-rays: galaxies

1. Introduction

In soft X-ray spectra of Active Galactic Nuclei (AGNs), a phenomenon called “soft X-ray excess” is often observed. Characterized by a similar and steep flux upturn towards lower energies, this feature is clearly noticed particularly in weakly-absorbed AGNs, such as type I Seyferts and Broad Line Radio Galaxies (BLRG). For years, the origin of this spectral structure has been unidentified, and many interpretations have been proposed. The simplest explanation is blackbody radiation from an optically-thick accretion disk. However, the observed color temperature of the soft excess, typically ~0.2 keV, is too high for such disks around black holes (BHs) of \( \gtrsim 10^7 M_\odot \) in mass, where \( M_\odot \) is the solar mass.

Given this, various alternative interpretations were proposed. Among them, mainly three ideas have been promising. One is absorption by a partially-covering and ionized absorber often incorporating velocity smearing effects (e.g., Gierlinski & Done 2004; Schurch & Done 2008; O’Neil et al. 2007); another is relativistically blurred reflection from an ionized disk that is in similar conditions as the first case (Zoghbi et al. 2010; Nardini et al. 2011); the other is a thermal Comptonization component that is separated from that producing the dominant Power-Law (PL) component (Marshall et al. 2003). Since these interpretations often degenerate in spectral analysis (Cerruti et al. 2011), there have been no conclusions concerning the origin of the soft X-ray excess in AGNs. Recently, however, Makishima et al. (2008) and Yamada (2011) established a Multi-Zone Comptonization (MZC) view for Cygnus X-1 (hereafter Cyg X-1) through an analysis of 0.5–200 keV Suzaku data, and showed that the last interpretation among the three indeed explains the soft excess (Frontera et al. 2001) seen in this leading black hole binary (BHB). This is analogous to the third interpretation of the AGN soft excess, as described above.

To examine the origin of the soft X-ray excess in AGNs utilizing the wide-band Suzaku capability, Noda et al. (2011b) chose the typical weakly-absorbed type 1 Seyfert galaxy Markarian 509 (Mrk 509 hereafter), and developed a method to study how its 0.5–3 keV intensity in the Suzaku data is correlated to that in 3–10 keV, and found that a significant positive offset remains in the softer band intensity when the correlation is extrapolated to lower counts. Because the method is based on the Count–Count Correlation with Positive Offset, hereafter, it is called the “C3PO” method for simplicity. Thus, utilizing time variations with the C3PO method, they extracted a stable soft X-ray component, and successfully explained it by a thermal Comptonization which is independent of the dominant PL continuum. When this soft Comptonization component is included, the time-averaged 0.5–45 keV spectrum of Mrk 509 was reproduced in terms of a weakly absorbed single PL and its reflection. In addition, Noda et al. (2011b) discovered that the new soft component varied on a timescale longer than 3d, independently of the PL variation. This securely excluded a competing interpretation of the detected soft component in terms of some largely extended thermal
Several AGNs

Table 1. Information of the five AGNs to be studied.

| Object name       | Type     | Obs. date       | Redshift | \(N_H\) (Gal)* | Reported \(R\)\dagger | Previous Suzaku study |
|-------------------|----------|-----------------|----------|----------------|------------------------|------------------------|
| Fairall 9         | Sy1      | 2007 Jun 7      | 0.047    | 0.031          | 0.52\(^{+0.20}_{-0.18}\) | Patrick et al. (2011)  |
|                   |          | 2010 May 19     |          |                | 1.55\(^{+0.26}_{-0.24}\) | Patrick et al. (2011)  |
| MCG –2–58–22      | Sy1.5    | 2009 Dec 2      | 0.047    | 0.027          | 0.69\(^{+0.05}_{-0.05}\) | Rivers, Markowitz, and Rothschild (2011) |
| 3C 382            | BLRG     | 2007 Apr 27     | 0.058    | 0.074          | 0.15\(^{+0.05}_{-0.05}\) | Sambruna et al. (2011) |
| 4C+74.26          | RLQ      | 2007 Oct 25     | 0.104    | 0.119          | 0.3–0.7                | Larsson et al. (2008)  |
| MR 2251–178       | RQQ      | 2009 May 7      | 0.064    | 0.024          | \(\leq 0.2\)            | Gofford et al. (2011)  |

* Equivalent hydrogen column density of the Galactic line-of-sight absorption in 10\(^22\) cm\(^{-2}\).
\dagger Reflection fraction defined by \(R = \Omega / 2\pi\), when \(\Omega\) is the reflection solid angle.

Fig. 1. Background-subtracted and dead-time corrected light curves of the five AGNs measured with XIS FI, in 0.5–3.0 keV represented by filled circles and 3–10 keV by open circles, shown with a binning of 10 ks. Open squares represent those of HXD-PIN in 15–45 keV, multiplied by a factor of 5 and with the same binning. 1\(\sigma\) errors of the data points of XIS FI are all less than 0.04 counts s\(^{-1}\). Dotted lines show the average 3–10 keV count rates.
emission from the host galaxy.

At the same time as Noda et al. (2011b), Mehdipour et al. (2011) analyzed multi-wavelength data of the same object, Mrk 509, which were obtained in a large campaign including XMM-Newton, Hubble, and FUSE. They obtained the same conclusion, that the soft X-ray excess of this AGN is created as a thermal Comptonization component that is independent of the principal PL continuum. Importantly, the parameters of the thermal Comptonization they derived, including an electron temperature of \( T_e \approx 0.2 \) keV, and an optical depth of \( \tau \approx 16 \), agree with those of Noda et al. (2011b). Thus, through the two independent methods (timing analysis and multi-wavelength spectral fitting), the soft excess phenomenon in Mrk 509 has been confirmed to arise as Comptonization by a warm corona, which is presumably different from (though possibly related to) the hotter corona producing the harder PL continuum. When combined with the Suzaku results on Cyg X-1 quoted above, this result strengthens the general analogy between BHs and AGNs.

The next step is to examine whether or not the same phenomenon as found in Mrk 509 and Cyg X-1 is present in a larger number of AGNs, including Seyferts and objects of other types. For this purpose, we utilize Suzaku archival datasets of AGNs, because the wide-band simultaneous coverage with Suzaku, typically available over a 0.5–45 keV band, is essential in determining the underlying continuum and the reflection component for each AGN, and hence to unambiguously identify the soft excess signals. In fact, many AGNs have been observed with Suzaku since its launch in 2005. However, the overall sample is neither complete nor homogeneous. Therefore, we choose to conduct the present study via the following two steps. The first is to define those AGN types which are suitable to our purpose. The second is to select, from the Suzaku archive, the best target that represents each of the selected classes.

In the present work, errors refer to \( \pm 1 \sigma \) confidence limits, except for model-fitting parameters in XSPEC for which 90% error ranges are adopted.

2. Target Selection

In order for the C3PO method developed in Noda et al. (2011b) to be applicable, the target AGNs should satisfy several conditions. First, we should exclude jet-dominated systems, like Blazars. This condition enables us to treat pure X-ray emission from a close vicinity of the central black hole (BH). Second, absorptions in our Galaxy and the host galaxies of AGNs should both be low enough to detect soft X-ray signals with significant statistics. Finally, reflection from accretion disks and other surrounding matter should be weak; our C3PO method utilizes count rates in the 3–10 keV bands as references, and should thus be dominated by continuum signals rather than reflection. Taking these conditions into account, we chose five AGN types: type 1 Seyfert galaxies (Sy1), type 1.5 Seyfert galaxies (Sy1.5), Broad Line Radio Galaxies (BLRGs), Seyfert-like Radio Loud Quasars (RLQs), and Radio Quiet Quasars (RQQs).

As representatives of Sy1, Sy1.5, BLRGs, RLQs, and RQQs, we chose Fairall 9, MCG –2–58–22, 3C 382, 4C +74.26, and MR 2251–178, respectively. Fairall 9, 3C 382, and MR 2251–178 are among the most typical and brightest objects in the currently available Suzaku datasets of respective types of AGNs. MCG –2–58–22 was selected because of its brightness, moderate absorption, and the longest net exposure, among the available Suzaku datasets of Sy1.5 (Rivers et al. 2011). 4C +74.26 was chosen because its X-ray spectrum is similar to those of Seyferts, and the jet contribution to its 0.5–45 keV signal is low (Kataoka et al. 2011). These AGNs were commonly reported to have mild reflection components, e.g., by Schmoll et al. (2009), Rivers, Markowitz, and Rothschild (2011), Sambruna et al. (2011), Larsson et al. (2008) and Gofford et al. (2011), who analyzed the same Suzaku datasets that we utilize. We summarize these objects in table 1. The Suzaku archive provides two datasets of Fairall 9, obtained in 2007 and 2010. Among them, we chose the first one for our analysis, because the object exhibited on this occasion a lower reflection fraction and a higher 3–10 keV flux than in the other.

3. Data Reduction

From the Suzaku (Koyama et al. 2007) and HXD (Takahashi et al. 2007) data of the 5 objects selected in section 2. These data, all acquired at the XIS nominal position, were prepared via version 2.0 processing in 2005, version 2.1 in 2007, and version 2.4 in 2009.

In the present analysis, the data of XIS 0, 2, and 3 (after 2006, XIS 0 and 3 only), which use front-illuminated (FI) CCD chips, were added and used as XIS FI. The data from XIS 1 were not analyzed, since it uses a back-illuminated CCD, and has a relatively high and unstable background. On-source events of the three or two XIS FI cameras were extracted from a circular region of 120” radius centered on the source. Background events were accumulated on a surrounding annular region of the same camera, with inner and outer radii of 180” and 270”, respectively. The response matrices and ancillary response files were produced by xisrmfgen and xissimarfgen (Ishisaki et al. 2007), respectively.

In a similar way, we prepared events of HXD-PIN. Non X-ray Background (NXB) contained in the data was estimated by analyzing a set of fake events that were created by a standard NXB model (Fukazawa et al. 2009). The on-source events and the NXB events were analyzed in the same manner, and the latter was subtracted from the former. In addition, the contribution from Cosmic X-ray Background (CXB: Boldt et al. 1987) was estimated and also subtracted from the on-source data. This was conducted using the HXD-PIN response to diffuse sources, assuming the spectral CXB surface brightness model determined by HEAO 1 (Gruber et al. 1999): \( E \times 10^{-9} \left( E/3 \text{ keV}\right)^{-0.29} \exp(-E/40 \text{ keV}) \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ keV}^{-1} \), where \( E \) is the photon energy. The estimated CXB count rate amounts to 5% of the NXB signals, in agreement with Kokubun et al. (2007).
Table 2. Parameters obtained by fitting 7 CCPs in figure 2 (a–i) and figures 3–6 (a–h) of the five individual AGNs with equation (1).*

| Object       | Energy range (keV) | $a$ (counts s$^{-1}$) | $b$ (counts s$^{-1}$) | $\chi^2$/d.o.f. |
|--------------|--------------------|-----------------------|-----------------------|-----------------|
| Fairall 9    | 0.5– 3             | $4.36 \pm 0.10$       | $0.51 \pm 0.21$       | 19.2/18         |
|              | 0.5– 0.8           | $0.23 \pm 0.04$       | $0.05 \pm 0.03$       | 21.1/18         |
|              | 0.8– 1             | $0.31 \pm 0.04$       | $0.10 \pm 0.03$       | 13.5/18         |
|              | 1– 1.2             | $0.44 \pm 0.05$       | $0.06 \pm 0.21$       | 16.0/18         |
|              | 1.2– 1.4           | $0.37 \pm 0.06$       | $0.09 \pm 0.05$       | 22.4/18         |
|              | 1.4– 1.7           | $0.55 \pm 0.07$       | $0.02 \pm 0.06$       | 23.9/18         |
|              | 1.7– 2             | $0.29 \pm 0.04$       | $0.05 \pm 0.03$       | 13.8/18         |
|              | 2– 3               | $0.48 \pm 0.07$       | $0.06 \pm 0.05$       | 24.6/18         |
|              | 0.5– 3             | $2.33 \pm 0.08$       | $0.33 \pm 0.13$       | 31.5/24         |
| MCG –2–58–22 | 0.5– 0.8           | $0.17 \pm 0.01$       | $0.01 \pm 0.02$       | 40.8/24         |
|              | 0.8– 1             | $0.25 \pm 0.02$       | $0.08 \pm 0.03$       | 39.3/24         |
|              | 1– 1.2             | $0.34 \pm 0.02$       | $0.08 \pm 0.03$       | 44.2/24         |
|              | 1.2– 1.4           | $0.37 \pm 0.02$       | $0.04 \pm 0.03$       | 33.2/24         |
|              | 1.4– 1.7           | $0.46 \pm 0.02$       | $0.05 \pm 0.03$       | 41.2/24         |
|              | 1.7– 2             | $0.29 \pm 0.01$       | $0.03 \pm 0.02$       | 20.8/24         |
|              | 2– 3               | $0.49 \pm 0.02$       | $0.04 \pm 0.03$       | 29.3/24         |
|              | 0.5– 3             | $3.78 \pm 0.26$       | $0.65 \pm 0.23$       | 21.6/23         |
| 3C 382       | 0.5– 0.8           | $0.14 \pm 0.02$       | $0.08 \pm 0.03$       | 25.4/23         |
|              | 0.8– 1             | $0.25 \pm 0.02$       | $0.08 \pm 0.03$       | 9.3/23          |
|              | 1– 1.2             | $0.27 \pm 0.03$       | $0.17 \pm 0.04$       | 18.7/23         |
|              | 1.2– 1.4           | $0.38 \pm 0.03$       | $0.04 \pm 0.04$       | 14.1/23         |
|              | 1.4– 1.7           | $0.37 \pm 0.06$       | $0.18 \pm 0.08$       | 48.8/23         |
|              | 1.7– 2             | $0.27 \pm 0.03$       | $0.06 \pm 0.04$       | 22.7/23         |
|              | 2– 3               | $0.53 \pm 0.05$       | $0 \pm 0.06$          | 23.7/23         |
|              | 0.5– 3             | $3.22 \pm 0.30$       | $0.48 \pm 0.17$       | 12.0/14         |
| 4C +74.26    | 0.5– 0.8           | $0.05 \pm 0.03$       | $0.04 \pm 0.02$       | 25.6/14         |
|              | 0.8– 1             | $0.06 \pm 0.03$       | $0.13 \pm 0.03$       | 16.6/14         |
|              | 1– 1.2             | $0.20 \pm 0.04$       | $0.10 \pm 0.04$       | 14.8/14         |
|              | 1.2– 1.4           | $0.32 \pm 0.03$       | $0.04 \pm 0.03$       | 8.0/14          |
|              | 1.4– 1.7           | $0.40 \pm 0.07$       | $0.08 \pm 0.06$       | 21.5/14         |
|              | 1.7– 2             | $0.19 \pm 0.05$       | $0.11 \pm 0.05$       | 26.2/14         |
|              | 2– 3               | $0.50 \pm 0.05$       | $0.04 \pm 0.05$       | 11.5/14         |
|              | 0.5– 3             | $1.39 \pm 0.22$       | $0.83 \pm 0.31$       | 31.4/26         |
| MR 2251–178  | 0.5– 0.8           | $0.08 \pm 0.03$       | $0.07 \pm 0.05$       | 19.8/26         |
|              | 0.8– 1             | $0.07 \pm 0.06$       | $0.17 \pm 0.09$       | 42.9/26         |
|              | 1– 1.2             | $0.16 \pm 0.06$       | $0.15 \pm 0.09$       | 27.7/26         |
|              | 1.2– 1.4           | $0.22 \pm 0.07$       | $0.11 \pm 0.10$       | 30.2/26         |
|              | 1.4– 1.7           | $0.36 \pm 0.05$       | $0.05 \pm 0.08$       | 12.7/26         |
|              | 1.7– 2             | $0.27 \pm 0.06$       | $-0.01 \pm 0.09$      | 27.4/26         |
|              | 2– 3               | $0.26 \pm 0.10$       | $0.30 \pm 0.14$       | 40.8/26         |

* Errors refer to 1σ confidence limits.
4. Data Analysis and Results

4.1. Extraction of Soft Excess Component

While a soft excess component was usually identified as excess signals above the PL determined by higher-energy spectral data, Noda et al. (2011b) formulated an independent way of doing this. Below, we follow their C3PO method. For this purpose, 0.5–3 keV (filled circles), 3–10 keV (open circles), and 15–45 keV (open squares, from HXD-PIN) light curves of the five AGNs are shown in figure 1, after subtracting the NXB. All of the XIS FI light curves exhibit more than 10% variations, with apparently tight correlations between the two XIS bands. To quantify this behavior, we produced Count–Count Plots (CCPs), in which the abscissa is the 3–10 keV band XIS FI count rates, and the ordinate is those in the 0.5–3 keV band. The results, shown in panel (a) of figure 2 to figure 7, indicate that the 0.5–3 keV count rate, denoted by $y$, varies linearly with that in 3–10 keV, $x$.

For further quantification, we fitted the data in each CCP with one straight line, expressed as

$$y = a x + b,$$  \hspace{1cm} (1)

where $a$ and $b$ were both left free. The fit goodness was evaluated in terms of chi-square statistics using errors expressed as $\sigma = \sqrt{\sigma^2 + (a \sigma_x)^2}$, where $\sigma_x$ and $\sigma_y$ are 1-σ statistical errors associated with $x$ and $y$, respectively.

As shown in table 2 and indicated in panel (a) of figures 2–6, the data distribution in each CCP has been successfully reproduced with equation (1). Therefore, the main variable component is considered to have varied without any change in its shape. In addition, the offset $b$ is significantly positive in all cases (2.4–2.8 $\sigma$), indicating that some signals should remain in the 0.5–3 keV bands, even when the intensity of the variable component becomes zero. This condition is the same as found with Mrk 509 by Noda et al. (2011b), and allows us to apply the C3PO method to the present five AGNs.

We divided the 0.5–3 keV band of the individual AGNs into seven finer bands, 0.5–0.8 keV, 0.8–1 keV, 1–1.2 keV, 1.2–1.4 keV, 1.4–1.7 keV, 1.7–2 keV, and 2–3 keV. Then, for each AGN, we created seven additional CCPs, where the abscissa is again the 3–10 keV count rate, while the ordinate is those in the seven finer soft X-ray bands. The obtained CCPs are presented in panels (b) to (h) of figure 2 to 6.

To examine the data distribution in each CCP representing a finer energy band, the fitting with one straight line, expressed by equation (1), was again performed. The obtained parameter values are summarized in table 2. Thus, the fit with equation (1) was successful in most of the 35 CCPs (the seven bands of the five objects). In all objects, furthermore, the CCPs generally exhibit positive offsets ($b > 0$), particularly in the lower energy bands. These offsets, divided by the corresponding energy intervals, define a spectrum that represents the non-varying soft X-ray signals of each AGN. In figure 7, we show these spectra in purple, after further normalizing to unabsorbed PL models with a photon index $\Gamma = 2$ of which the normalizations were chosen to approximately reproduce the observed time-averaged spectra of the corresponding objects.

To quantify these stable soft emission (hereafter SSE) spectra, we fitted them with five representative models: power law (powerlaw), multi-color disk (diskbb; Mitsuda et al. 1984) emission, thin-thermal plasma radiation (apec; Smith et al. 2001), relativistically smeared and ionized reflection (kdblur * reflionx: Laor 1991; Ross & Fabian 2005), and thermal Comptonization (comptt: Titarchuk 1994). The fits all included the Galactic line-of-sight absorption, which was modeled by wabs (Morrison & McCammon 1983) with the $N_H$ values given in table 1. In fitting with the apec model, the abundance parameter was fixed at 0.5 solar, while the temperature and the normalization were left free. In the kdblur * reflionx model, the photon index of the primary continuum for reflection was fixed at 2, and the inner and outer disk radii at 1.24 $R_g$ and 400 $R_g$, respectively. The emissivity index was also fixed at 4. The other parameters (the inner radius, the ionization parameters, and the normalization) were all left free. In the comptt fit, the seed photon temperature was fixed at 0.02 keV, while the other parameters were left free. The redshifts in those models were fixed at the values given in table 1. The obtained fit parameters are summarized in table 3, which also gives the 0.5–3 keV luminosity of this component calculated by the apec model. Thus, the five SSE spectra can be successfully reproduced by any of the employed five models. They are characterized by a PL photon index of $\sim 3$, or a disk temperature of $\sim 0.3$ keV, or a apec temperature of $\sim 1.2$ keV. If employing the relativistically blurred and ionized reflection model, the ionization parameter became $\sim 50$ erg cm$^{-2}$ s$^{-1}$, with the inner disk radius fixed at 1.24 $R_g$. When employing the thermal Comptonization model with a seed photon temperature of 0.02 keV, which can be calculated from the mass of a typical central BH of $\sim 10^8 M$, and an Eddington ratio of $\sim 10\%$, the coronal temperature becomes 0.3–1 keV and the optical depth $\gtrsim 15$. Below, we do not consider the diskbb modeling, since its temperature is too high, as pointed out previously (section 1). The PL modeling may not be considered either, because the indicated steep PL does not accept easy interpretations. In other words, we retain the apec, kdblur * reflionx, and comptt modelings.

In an attempt to extend our analysis to the HXD data, we additionally show in figure 1 15–45 keV light curves of the five AGNs obtained with HXD-PIN. The CCPs of these bands against the 3–10 keV XIS counts are shown in panels (i) of figures 2–6. The results of fitting these CCPs with equation (1) are given in table 2, except for MR 2251–178 in which the data points have too large errors, and the variation is too small to derive meaningful constraints on the parameters $a$ and $b$. Thus, the hard-band CCPs of Fairall 9 and MCG –2–58–22 suggest statistically significant positive offsets (though with large errors), so we divided them by the energy range of 20 keV, and show the results in figure 7 as ratios to the same $\Gamma = 2$ PL. Hereafter, these hard-band components derived with the HXD vs. XIS C3PO method are called stable hard emissions (SHEs).
Fig. 2. CCPs of Fairall 9. Abscissa gives NXB-subtracted XIS FI count rate in 3–10 keV, while ordinate gives that in (a) 0.5–3 keV, (b) 0.5–0.8 keV, (c) 0.8–1.0 keV, (d) 1.0–1.2 keV, (e) 1.2–1.4 keV, (f) 1.4–1.7 keV, (g) 1.7–2.0 keV, (h) 2.0–3.0 keV, and (i) 15–45 keV. All data are binned into 10 ks. The error bars represent the statistical ±1σ range. The dotted straight line refers to equation (1).

Fig. 3. Same as figure 2, but of MCG –2–58–22.
Fig. 4. Same as figure 2, but of 3C 382.

Fig. 5. Same as figure 2, but of 4C +74.26.
4.3. Time-Averaged Spectrum Analysis

In subsections 4.1 and 4.2, we followed the C3PO method of Noda et al. (2011b), and utilized time variations to extract the three distinct spectral components; the SSE and SHE components (purple in figure 7), and the variable (absorbed) PL component (figure 8). Then, can we arrive at the same spectral decomposition by analyzing the time-averaged (i.e., High-phase plus Low-phase) wide-band spectra of our sample objects? To see this, we fitted these spectra with a model of wabs * zxipcf * (cutoffpl + pexrav + zgauss). Here, pexrav represents a reflection continuum from neutral matter (Magdziarz & Zdziarski 1995), and zgauss an Fe Kα line. zxipcf (Reeves et al. 2008) represents the absorption by an ionized (or “warm”) absorber, with its equivalent hydrogen column density, the ionization parameter, $\xi$, and covering fraction left as free parameters. This follows Weaver et al. (1995), Sambruna et al. (2011), Kaspi et al. (2004), and Gofford et al. (2011), who reported the presence of warm absorbers in MCG −2–58–22, 3C 382, 4C +74.26, and MR 2251–178, respectively. For Fairall 9, a broad iron line component laor (Laor 1991) was added, while the zxipcf factor was excluded because this is considered to be a bare-nucleus object (e.g., Schmoll et al. 2008; Patrick et al. 2011). In addition, for MR 2251–178 which was reported to exhibit absorption by outflows
Fig. 7. The High (black) and Low (red) spectra of the present sample AGNs, shown as a ratio to a common unabsorbed $\Gamma = 2$ PL. Purple shows the SSE and SHE spectra of each object determined by $b$ of table 2, presented after divided by the same PL as used to normalize the High and Low spectra.

(Gofford et al. 2011), we added three Gaussians with free $\sigma$ and negative normalization, to represent a Fe I–XVI M-shell unresolved transition forest (at a center energy of $E_c = 0.77$ keV), as well as those from Fe XXIV L-shell ($E_c = 1.29$ keV) and Fe XXV–XXVI K-shell ($E_c = 7.57$ keV), and fitted with a model of $\text{wabs} \times \text{zxipcf} \times (\text{cutoffpl} + \text{pexrav} + \text{zgauss} + 3 \times \text{zgauss})$. The cutoff energies were fixed at 200 keV, except for MR 2251–178 in which it was fixed at 100 keV after Gofford et al. (2011). The redshifts in these models were all fixed at the values given in table 1. As a result, we obtained $\chi^2$/d.o.f. of 1105.61/658 for Fairall 9, 1099.49/844 for MCG–2–58–22, 1070.05/846 for 3C 382, 666.18/605 for 4C +74.26, and 1581.01/871 for MR 2251–178: all the five AGNs, except for 4C +74.26, rule out the simple PL-based modeling. These fit failures in fact arise mainly due to data excess above the model in soft X-rays, which does not vanish even when the absorbing column density is left free to vary. Through this “static” spectral analysis, we have thus confirmed the presence of a soft excess component, in at least four of our sample objects.
Signals, we first employed the thin-thermal plasma model, and then the disk blackbody model, to fit the soft X-ray spectra of AGNs. The cutoff power-law normalization at 1 keV, in units of $10^{33}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$, is constrained by the disk blackbody model. The apec model, with the ionization parameter, $n_H$, and the electron and H densities, $n_e$ and $n_H$, respectively, is constrained by the cutoff power-law model. The reflionx model, with the inner disk radius, $r$, and the inner disk height, $h$, is constrained by the cutoff power-law model. The compTT model, with the temperature, $T_e$, and the ionization parameter, $n_H$, is constrained by the cutoff power-law model. The kdblur model, with the inner disk radius, $r$, and the inner disk height, $h$, is constrained by the cutoff power-law model. The Model Parameter Table 3 shows the parameters obtained by fitting the SSE spectra of the five AGNs in Figure 7. Table 4 shows the parameters obtained in the fits to 0.5–45 keV difference spectra of the five AGNs. In order to improve these spectral fits, we tried adding a soft excess model, expressed by a thin-thermal plasma model, an ionized and relativistically-blurred reflection model, or a thermal Compton model, which can represent the SSE (subsection 4.1). Because hot plasma emission in the host galaxies is generally expected in the soft X-ray band of AGN signals, we first employed the thin-thermal plasma model, apec, and revised the fitting model to a form of wabs * zxpircf * (cutoffpl + pexrav + gauss + apec). As before, Fairall 9 and MR 2251–178 were fitted with wabs * (cutoffpl + pexrav + gauss + laor + apec), and wabs * zxpircf * (cutoffpl + pexrav + gauss + 3 * gauss + apec), respectively. In these fits, the temperature, abundance and normalization of apec were all left free. Then, as shown in Table 5 and Figure 9, the time-averaged spectra of Fairall 9, MCG–2–58–22, 3C 382, and 4C+74.26 were successfully reproduced, while that of MR 2251–178 was not, mainly due to residuals in the soft X-ray band. Furthermore, even for the successful four objects, the obtained abundances (Table 5) are much lower than the solar value, making the fits physically unrealistic. Thus, the thin-thermal emission model, which was allowed by
Fig. 8. Difference spectra of the AGNs in vF_2 forms, obtained by subtracting Low-phase from High-phase spectra, and fitted by wabs * cutoffpl. The lower panels show residuals from the best-fit model.

This SSE modeling, becomes unsuccessful when the time-averaged spectra are considered.

As a next attempt, we replaced the apec model with an ionized reflection model, reflionx, but first without relativistic blurring, and tried to reproduce the time-averaged spectra with wabs * zxipcf * (cutoffpl + pexrav + zgauss + reflionx), except for Fairall 9, which was fitted with wabs * (cutoffpl + pexrav + zgauss + laor + reflionx), and MR 2251–178 with wabs * zxipcf * (cutoffpl + pexrav + zgauss + 3 x zgauss + reflionx). The ionization parameter and the normalization of reflionx were left free, while the photon index of its primary continuum was tied to that of cutoffpl. Because the ionized reflection model is inevitably accompanied by a strong hard X-ray hump, even when \( \xi \) is made very large (e.g., \( > 10^3 \)), the spectral soft excess was not fully accounted for by the reflionx model. Specifically, the fits were unsuccessful, except for 4C +74.26, with \( \chi^2/\text{d.o.f.} \) of 1083.54/657, 1049.98/842, 1206.17/846, 692.57/603, and 1161.51/866 for Fairall 9, MCG –2–58–22, 3C 382, 4C +74.26, and MR 2251–178, respectively. The fits are thus even worse than those with the apec modeling.
Table 5. The results of fitting the time-averaged spectra of the five AGNs, wherein the soft excess is represented by an apec model.

| Model     | Parameter | Fairall 9 | MCG−2–58−22 | 3C 382 | 4C+74.26 | MR 2251−175 |
|-----------|-----------|-----------|-------------|--------|----------|-------------|
| wabs      | $N_H$     | 0.032 (fix) | 0.035 (fix) | 0.074 (fix) | 0.21$^{+0.03}$ _$-$0.01 | 0.028 (fix) |
| xzipcf    | $N_H$     | —         | 7.27$^{+5.52}$ _$-$4.41 | 0.07$^{+0.19}$ _$-$0.02 | 1.36$^{+0.28}$ _$-$0.05 | 1.07$^{+0.02}$ |
| log $\xi$ | —         | 4.35$^{+1.63}$ _$-$0.57 | 2.5$^{+7.53}$ _$-$0.16 | 0.53$^{+0.11}$ _$-$0.09 | 0.40$^{+0.01}$ _$-$0.03 |
| Cvr frac. | —         | 0.58$^{+0.12}$ _$-$0.38 | > 0.62 | 0.61$^{+0.04}$ _$-$0.05 | 0.86$^{+0.01}$ _$-$0.02 |
| powerlaw  | $\Gamma$  | 1.99$^{+0.02}$ _$-$0.03 | 1.85$^{+0.01}$ _$-$0.01 | 1.82$^{+0.01}$ _$-$0.01 | 1.10$^{+0.06}$ _$-$0.08 | 1.15$^{+0.06}$ _$-$0.01 |
| pexrav    | $f_{ref}$ | 1.9$^{+0.3}$ _$-$0.1 | 1.8$^{+0.1}$ _$-$0.1 | 1.1$^{+0.01}$ _$-$0.1 | 1.1$^{+0.01}$ _$-$0.1 |
| Fe $\perp$ | $E_c$     | 6.37$^{+0.02}$ _$-$0.03 | 6.25$^{+0.02}$ _$-$0.01 | 6.41$^{+0.03}$ _$-$0.03 | 6.40$^{+0.04}$ _$-$0.04 | 6.38$^{+0.04}$ _$-$0.03 |
|           | $\sigma$  | 10$^{-4}$ (fix) | 10$^{-4}$ (fix) | 0.099$^{+0.032}$ | 10$^{-4}$ (fix) | 10$^{-4}$ (fix) |
|           | $N_{Fe}$  | 2.30$^{+0.21}$ _$-$0.22 | 1.84$^{+0.32}$ _$-$0.32 | 2.25$^{+0.44}$ _$-$0.43 | 1.42$^{+0.35}$ _$-$0.34 | 1.15$^{+0.30}$ _$-$0.29 |
|           | $EW$      | 77$^{+40}$ _$-$32 | 33$^{+54}$ _$-$32 | 49$^{+27}$ _$-$32 | 30$^{+32}$ _$-$12 | 21$^{+8}$ _$-$8 |
| laor      | $E_c$     | 6.37$^{+0.07}$ _$-$0.07 | — | — | — | — |
|           | $R_{in}$  | 16.7$^{+2.0}$ _$-$7.8 | — | — | — | — |
|           | $N_{Fe}$  | 1.67$^{+0.57}$ _$-$0.50 | — | — | — | — |
|           | $EW$      | 204$^{+56}$ _$-$20 | — | — | — | — |
| apec      | $kT$      | 0.32$^{+0.02}$ _$-$0.02 | 0.18$^{+0.02}$ _$-$0.03 | 0.25$^{+0.03}$ _$-$0.04 | 0.68$^{+0.08}$ _$-$0.07 | 0.31$^{+0.01}$ |
|           | $A[Z_\odot]$ | < 0.005 | < 0.007 | < 0.004 | < 0.005 | 0.002$^{+0.001}$ |
|           | $N_{apec}$ | 0.52$^{+0.15}$ _$-$0.12 | 1.41$^{+0.64}$ _$-$0.42 | 1.09$^{+0.45}$ _$-$0.24 | 0.73$^{+0.09}$ _$-$0.12 | 8.06$^{+1.47}$ _$-$0.87 |

$\chi^2$/d.o.f. = 728.62/651 846.70/832 883.80/842 612.45/601 983.20/865

* Equivalent hydrogen column density in $10^{22}$ cm$^{-2}$ for the Galactic or the intrinsic line-of-sight absorption.
† The power-law normalization at 1 keV, in units of $10^{-5}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV.
‡ Center energy in keV in the rest frame.
§ The Gaussian normalization in units of $10^{-5}$ photons cm$^{-2}$ s$^{-1}$.
∥ Center energy in units of keV.
¶ The laor normalization in units of $10^{-2}$ photons cm$^{-2}$ s$^{-1}$.
** The apec normalization, in units of $10^{-15}/A_{\odot}(1+z)^2\int n_e n_H dV$, where $D_A$ is the angular size distance to the source (cm), $n_e$ and $n_H$ are the electron and H densities (cm$^{-3}$).

Given this, the reflionx component in the above fits were convolved with the relativistic smearing kernel, kdblur, with the emissivity index and the inner disk radius left free, while the outer radius was fixed at 400 $R_g$. Then, as summarized in table 6 and shown in figure 10, the fits to the time-averaged spectra of all five AGNs were much improved, and became acceptable for four sources, except MR 2251−178.

In the above successful fits to the 4 sources (figure 10), the soft-band (< 2 keV) excess is explained by the kdblur * reflionx * component, while that in the hard band by kdblur * reflionx + pexrav. Furthermore, the PL continua of the 4 sources (table 6), against which these soft and hard excesses are defined, are found to be consistent with their High-Low difference spectra (the main variable component; table 4, figure 4). Therefore, the two reflection models, jointly describing the static excess above the PL, should also be able to explain their SSE and SHE data points, which were determined by out dynamical C3PO analysis. To examine this idea, we compared the kdblur * reflionx + pexrav components in figure 9 with the SSE+SHE data points (in purple), in terms of chi-square evaluation, but without any parameter readjustment. As a result, good agreements were obtained in Fairall 9 and 3C 382, with $\chi^2$/d.o.f. of 4.95/8 and 11.14/8, respectively, while poor results in MCG−2–58–22 (19.79/8) and 4C+74.26 (23.50/8). Thus, the kdblur * reflionx + pexrav modeling failed to explain the time-averaged spectrum of one source (MR 2251−178), and caused inconsistencies between the static and dynamic results on two more sources (MCG−2–58–22 and 4C+74.26).

Finally, we replaced the kdblur * reflionx model with the thermal Comptonization model, compTT, and fitted the time-averaged spectra with a model of wabs * xzipcf * (cutoffpl + pexrav + zgauss + compTT), except for Fairall 9 which was fitted with wabs * xzipcf * (cutoffpl + pexrav + zgauss + laor + compTT), and MR 2251−178 with wabs * xzipcf * (cutoffpl + pexrav + zgauss + 3 * zgauss + compTT). In these fits, the disk temperature was fixed at 0.02 keV, as before, and the electron temperature of compTT at 0.5 keV, following Noda et al. (2011b) and Mehdiipour et al. (2011), while its optical depth and normalization were left free. Like in the apec modeling (figure 9), any hard-band excess above the PL is now represented solely by cold reflection (pexrav). As summarized in table 7 and shown in figure 11, all of
Table 6. The same as table 5, but the soft excess is represented by ionized and relativistically-blurred reflection (kdblur + reflionx) instead of apec.

| Model   | Parameter | Fairall 9 | MCG –258–22 | 3C 382 | 4C +74.26 | MR2251–175 |
|---------|-----------|-----------|--------------|---------|-----------|-------------|
| wabs    | $N_H$     | 0.032 (fix) | 0.035 (fix) | 0.074 (fix) | 0.24 ± 0.02 | 0.028 (fix) |
| zxipcf  | $N_H$     | —         | <0.36       | <0.12   | 0.24 ± 0.07 | 3.15 ± 0.02 |
|         | log $\xi$ | —         | 0.73 ± 0.32 | 2.52 ± 0.16 | 2.26 ± 0.16 | 2.16 ± 0.06 |
|         | Cvr frac. | —         | <0.25       | >0.43   | >0.43      | 0.65 ± 0.15 |
| powerlaw| $\Gamma$  | 1.99 ± 0.03 | 1.84 ± 0.02 | 1.82 ± 0.02 | 1.92 ± 0.06 | 1.83 ± 0.01 |
|         | $N_{PL}$  | 0.74 ± 0.01 | 1.22 ± 0.02 | 1.04 ± 0.01 | 0.99 ± 0.06 | 1.23 ± 0.04 |
| pexrav  | $f_{ref}$ | 0.8 ± 0.3  | <0.3        | <0.2    | <0.5       | <0.2        |
| Fe 1 Ka | $E_c$     | 6.36 ± 0.04 | 6.39 ± 0.03 | 6.42 ± 0.04 | 6.39 ± 0.04 | 6.46 ± 0.04 |
|         | $\sigma$  | 10^{-4} (fix) | 10^{-4} (fix) | 0.095 ± 0.025 | 10^{-4} (fix) | 10^{-4} (fix) |
|         | $N_{Fe}$  | 2.48 ± 0.25 | 2.01 ± 0.21 | 2.25 ± 0.44 | 1.46 ± 0.31 | 0.91 ± 0.25 |
|         | $EW$ (eV) | 91 ± 40  | 33 ± 44     | 52 ± 27  | 37 ± 12    | 25 ± 12     |
| kdblur  | $q^*$     | 4.48 ± 2.70 | 5.15 ± 4.19 | 4.87 ± 1.11 | 3.96 ± 0.89 | 2.45 ± 0.21 |
|         | $R_{in}$  | 2.30 ± 0.49 | 1.24 ± 0.35 | 2.44 ± 0.56 | 1.24 ± 0.31 | 1.24 ± 0.27 |
| reflionx| $\xi$     | 58.9 ± 27.2 | 101.8 ± 53.2 | 103.5 ± 56.6 | 94.1 ± 42.9 | 20.2 ± 12 |
|         | $N_{refl}x$† | 3.11 ± 4.34 | 4.97 ± 0.64 | 2.39 ± 0.45 | 2.44 ± 0.12 | 1.28 ± 0.23 |

$\chi^2$/d.o.f. 785.06/651 945.79/832 886.26/842 660.51/601 1145.17/865

* The emissivity index (scales as $R^{-\xi}$).
† The ionization parameter, in units of erg cm s^{-1}.
‡ The reflionx normalization, in units of 10^{6} photons keV^{-1} cm^{-2} s^{-1} at 1 keV.

Table 7. The same as table 5, but the soft excess is represented by thermal Comptonization component (comptt) instead of apec.

| Model   | Parameter | Fairall 9 | MCG –258–22 | 3C 382 | 4C +74.26 | MR2251–175 |
|---------|-----------|-----------|--------------|---------|-----------|-------------|
| wabs    | $N_H$     | 0.032 (fix) | 0.035 (fix) | 0.074 (fix) | 0.24 ± 0.02 | 0.028 (fix) |
| zxipcf  | $N_H$     | —         | <0.36       | <0.12   | 0.24 ± 0.07 | 3.15 ± 0.02 |
|         | log $\xi$ | —         | 0.73 ± 0.32 | 2.52 ± 0.16 | 2.26 ± 0.16 | 2.16 ± 0.06 |
|         | Cvr frac. | —         | <0.25       | >0.43   | >0.43      | 0.65 ± 0.15 |
| powerlaw| $\Gamma$  | 1.99 ± 0.03 | 1.84 ± 0.02 | 1.82 ± 0.02 | 1.92 ± 0.06 | 1.83 ± 0.01 |
|         | $N_{PL}$  | 0.74 ± 0.01 | 1.22 ± 0.02 | 1.04 ± 0.01 | 0.99 ± 0.06 | 1.23 ± 0.04 |
| pexrav  | $f_{ref}$ | 0.9 ± 0.3  | <0.4        | <1.6    | <0.3       | <0.1        |
| Fe 1 Ka | $E_c$     | 6.37 ± 0.04 | 6.26 ± 0.08 | 6.43 ± 0.03 | 6.41 ± 0.04 | 6.40 ± 0.04 |
|         | $\sigma$  | 10^{-4} (fix) | 10^{-4} (fix) | 0.099 ± 0.031 | 10^{-4} (fix) | 10^{-4} (fix) |
|         | $N_{Fe}$  | 2.30 ± 0.21 | 1.89 ± 0.32 | 2.18 ± 0.41 | 1.46 ± 0.34 | 1.12 ± 0.29 |
|         | $EW$ (eV) | 84 ± 15 | 34 ± 54     | 48 ± 32  | 34 ± 20 | 21 ± 15 |
| laor    | $E_c$     | 6.37 ± 0.06 | —           | —       | —          | —           |
|         | $R_{in}$  | 16.2 ± 22.8 | —           | —       | —          | —           |
|         | $N_{Fe}$  | 2.01 ± 0.47 | —           | —       | —          | —           |
|         | $EW$ (eV) | 91 ± 51 | —           | —       | —          | —           |
| comptt  | $T_0$ (keV) | 0.02 (fix) | —           | —       | —          | —           |
|         | $kT$ (keV) | 0.5 (fix) | —           | —       | —          | —           |
|         | $\tau$   | 13.7 ± 0.79 | 16.2 ± 1.4  | 15.6 ± 0.44 | 18.5 ± 0.27 | 13.7 ± 0.42 |
|         | $N_{Comp}$* | 0.39 ± 0.08 | 0.66 ± 0.15 | 2.27 ± 0.34 | 3.25 ± 2.35 | 42.2 ± 26.7 |

$\chi^2$/d.o.f. 721.33/652 825.32/833 894.07/843 624.26/602 929.15/866

* The thermal Comptonization component normalization, in units of photons keV^{-1} cm^{-2} s^{-1} at 1 keV.
Fig. 9. Fits to the time-averaged spectra of the five AGN, with models of $w_{\text{abs}} \times (\text{cutoffpl} + \text{pexrav} + \text{zgauss} + \text{laor} + \text{apec})$ for Fairall 9, $w_{\text{abs}} \times \text{zxp} \times (\text{cutoffpl} + \text{pexrav} + \text{zgauss} + 3 \times \text{zgauss} + \text{apec})$ for MR 2251–178, and $w_{\text{abs}} \times \text{zxp} \times (\text{cutoffpl} + \text{pexrav} + \text{zgauss} + \text{apec})$ for the others, respectively. The SSE and SHE components are also shown in purple.

the fits are acceptable, and the fit goodness is significantly (except 3C 382) better than those in table 6. Thus, the soft excess component, identified statically in each object using its time-averaged spectrum, can be reproduced by the Comptonization model. Furthermore, in these fits, the $\text{comptt}$ component has a very similar shape and intensity to the SSE spectrum. Actually, when the best-fit $\text{comptt}$ model is compared (again without any parameter readjustment) with the SSE data points, we obtain a $\chi^2$/d.o.f. of 4.01/7 for Fairall 9, 10.02/7 for MCG –2–58–22, 9.52/7 for 3C 382, 9.51/7 for 4C +74.26, and 5.97/7 for MR 2251–178, which are all acceptable. Therefore, the soft excess structure in the time-averaged spectrum and the dynamically extracted SSE spectrum can be regarded as two different manifestations of the same spectral component, which is considered to arise via the thermal Comptonization process.

Similarly, the SHE flux point of four sources (except MR 2251–178) appear to be consistent with the pexrav
component. In fact, these SHE data points for Fairall 9 and MCG–2–58–22 have +2.1 and +5.7σ significances above zero, respectively, while they deviate from the pexrav model predictions by 1.0 and 2.8σ, respectively. Similarly, the SHE data points of 3C 382 and 4C +74.26 (which are both statistically insignificant) deviate from their pexrav predictions by only 0.1 and 0.8σ, respectively. Thus, the dynamically derived SHE can be identified (within the large errors) with the pexrav model required by the time-averaged spectrum.

5. Discussion

To study the origin of soft excess phenomena, five AGNs with different types were selected from the Suzaku archive, and analyzed; Fairall 9 (Sy1), MCG–2–58–22 (Sy1.5), 3C 382 (BLRG), 4C +74.26 (RLQ), and MR 2251–178 (RQQ), which

Fig. 10. Same as figure 9, but with the apec model replaced by a kdblur * reflionx model. The spectrum of Fairall 9 was fitted with wabs *(cutoffpl + pexrav + zgauss + kdblur + reflionx), and that of MR 2251–178 was with wabs * zxipcf *(cutoffpl + pexrav + zgauss + 3 * zgauss + kdblur + reflionx), while those of the others were with wabs * zxipcf *(cutoffpl + pexrav + zgauss + kdblur + reflionx).
have X-ray signals dominated by emission from their central engines. Applying the C3PO method developed in Noda et al. (2011b) and Churazov, Gilfanov, and Revnivtsev (2001), who detected an SSE in the bright Sy1 Mrk 509 and the typical BHB Cyg X-1, respectively, we succeeded to extract an SSE in the 0.5–3 keV band of all the five AGNs. In addition, applications of the same technique to the 15–45 keV HXD-PIN data allowed us to detect the SHE from at least two of the five AGNs.

The highly linear CCPs we obtained rule out possibilities that the soft X-ray variations of our sample AGNs are caused by changes in any absorption, including in particular a partially covering warm absorber, which is one of the three main interpretations for explaining the soft excess phenomena of AGNs (section 1). This is because a partially covering absorber, if variable in its covering fraction, column density, or ionization degree, would cause complex spectral changes, so the CCP would not show such a linear distribution as in figures 2–6. Furthermore, in this case the soft X-ray count would vanish.
appears both at the softest and hardest spectral ends. When the reflection signals from an ionized disk are expected to energy coverage with Suzaku is particularly important, because whether or not this interpretation is appropriate, the broad would not necessarily have to follow variations of the primary “light bending” effect (e.g., Miniutti et al. 2007), the reflection

When a fine-tuned geometry is actually realized to enable the fit to MR 2251

the time-averaged HXD data. This effect indeed made the

Fig. 12. The 0.5–3 keV luminosity of the SSE component (table 3) of the five AGNs, plotted against their 3–10 keV luminosity. Those of Mrk 509 reported in Noda et al. (2011b) are also calculated and plotted.

without leaving a positive offset, when the PL intensity becomes zero. Thus, the SSEs must be more independent of the PL continuum.

The SSE spectra, extracted from the five AGNs via the C3PO analysis, were reproduced successfully by five spectral models; PL, diskbb, apec, kdblur * reflionx, and comptt. From physical considerations, two of them, the PL and diskbb, were ruled out. Combining the static analysis with the dynamical one, apec was found to be unrealistic. Furthermore, as given in figure 12, the measured 0.5–3 keV luminosity of the SSE of our AGNs is too high for thermal emission from their host galaxies (which would be at most \(10^{43} \text{erg s}^{-1}\); e.g., Fukazawa et al. 2006), and correlates positively with the AGN luminosity. Therefore, the SSE must be tightly connected to the AGN phenomenon, rather than to the host galaxies.

How about the relativistically-smeared and ionized reflection interpretation modeled by kdblur * reflionx? When a fine-tuned geometry is actually realized to enable the “light bending” effect (e.g., Miniutti et al. 2007), the reflection would not necessarily have to follow variations of the primary emission, and may remain stable, like the SSE. To examine whether or not this interpretation is appropriate, the broad energy coverage with Suzaku is particularly important, because the reflection signals from an ionized disk are expected to appear both at the softest and hardest spectral ends. When figure 10 is closely examined, we find that the model invoking kdblur * reflionx + pexrav tends to under-predict the < 3 keV portion of the time-averaged data, and over-predict the time-averaged HXD data. This effect indeed made the fit to MR 2251–178 unacceptable. Furthermore, at least in MCG –2–58–22 and 4C +74.26, the kdblur * reflionx + pexrav component determined through our static analysis was not able to explain the dynamically determined SSE + SHE signals. Thus, the relativistic reflection interpretation cannot explain the broad-band Suzaku data of three out of the 5 AGNs. In contrast, the thermal Comptonization interpretation, using comptt, can consistently explain, in all of the 5 AGNs, both the dynamically derived SSE and the static soft excess. This agreement between the two independent methods significantly strengthens the determination of the soft excess signals (or the SSE) in our sample AGNs. In this case, the SHE can be explained as a separate component arising from a cold reflector that is most likely located at a considerable distance from the central engine.

Presuming that the SSE is produced as a thermal Comptonization component that is separate from (but related to) the dominant PL, the corona of each AGN is then considered to consist of multiple regions having different optical depths and/or temperatures, namely, different Compton y-parameters. This may be called the Multi-Zone Comptonization (MZC) condition. Since the various types of AGNs that have been selected in the present paper all have X-ray signals dominated by non-jet continua, their central engines (where most of the gravitational energy is converted to radiation) are inferred to be in the MZC condition. This agrees with the previous results on Mrk 509 (Noda et al. 2011b; Mehdipour et al. 2011), and the leading BHB Cyg X-1 (e.g., Makishima et al. 2008; Yamada 2011). The lack of significant short-term (< several hundred ks) variability in the SSE may be explained if the SSE-producing Compton corona is largely (> several hundred gravitational radii) extended, or more likely, if the seed-photon flux (presumably from the disk) is stable on these time scales, while the dominant PL variations are produced in those part of the corona with the largest y-parameter (Makishima et al. 2008). Overall, we suggest that the soft excess emission of some (if not all) AGNs is actually a part of its primary continuum, produced in grossly the same central engine as the PL component, but possibly at somewhat different locations, considering the clear difference in their variation characteristics. In this interpretation, the SHE is considered to have a different origin from the SSE, and produced via reflection by distant cool materials, as represented by pexrav.

The present results have impacts not only on the central engine, but also on the determination and interpretation of various secondary spectral components, including disk reflection, iron lines, and warm absorbers. This is because the MZC condition affects the primary continuum shape, which was often assumed conventionally as a single PL. For example, Noda et al. (2011a) found that the iron Kα-line width of the type I Seyfert, MCG –6–30–15, decreases considerably when including a hard component, which varied independently of the dominant PL and made the primary continuum concave.

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References

Boldt, E. 1987, Phys. Rep., 146, 215
Cerruti, M., Ponti, G., Boisson, C., Costantini, E., Longinotti, A. L.,
Matt, G., Mouchet, M., & Petrucci, P. O. 2011, A&A, 535, A113
Churazov, E., Gilfanov, M., & Revnivtsev, M. 2001, MNRAS, 321,
759
Dickey, J. M., & Lockman, F. J. 1990, ARA & A, 28, 215
Frontera, F., et al. 2001, ApJ, 550, L47
Fukazawa, Y., et al. 2009, PASJ, 61, S17
Fukazawa, Y., Botoya-Nonesa, J. G., Pu, J., Ohto, A., & Kawano, N.
2006, ApJ, 636, 698
Gierlinski, M. G., & Done, C. 2004, MNRAS, 349, L7
Gofford, J., et al. 2011, MNRAS, 414, 3307
Gruber, D. E., Matteson, J. L., Peterson, L. E., & Jung, G. V. 1999,
ApJ, 520, 124
Ishisaki, Y., et al. 2007, PASJ, 59, S113
Kaspi, S., Netzer, H., Chelouche, D., George, I. M., Nandra, K., &
Turner, T. J. 2004, ApJ, 611, 68
Kataoka, J., et al. 2011, ApJ, 740, 29
Kokubun, M., et al. 2007, PASJ, 59, S53
Koyama, K., et al. 2007, PASJ, 59, S23
Laor, A. 1991, ApJ, 376, 90
Larsson, J., Fabian, A. C., Ballantyne, D. R., & Miniutti, G. 2008,
MNRAS, 388, 1037
Magdziarz, P., & Zdziarski, A. A. 1995, MNRAS, 273, 837
Makishima, K., et al. 2008, PASJ, 60, 585
Marshall, H. L., Edelson, R. A., Vaughan, S., Malkan, M., O'Brien, P.,
& Warwick, R. 2003, ApJ, 125, 459
Mehdipour, M., et al. 2011, A&A, 534, A39
Miniutti, G., et al. 2007, PASJ, 59, S315
Mitsuda, K., et al. 1984, PASJ, 36, 741
Mitsuda, K., et al. 2007, PASJ, 59, S1
Morrison, R., & McCammon, D. 1983, ApJ, 270, 119
Nardini, E., Fabian, A. C., Reis, R. C., & Walton, D. J. 2011, MNRAS,
410, 1251
Noda, H., Makishima, K., Uehara, Y., Yamada, S., & Nakazawa, K.
2011a, PASJ, 63, 449
Noda, H., Makishima, K., Yamada, S., Torii, S., Sakurai, S., &
Nakazawa, K. 2011b, PASJ, 63, S925
O’Neill, P. M., Nandra, K., Cappi, M., Longinotti, A. L., & Sim, S. A.
2007, MNRAS, 381, L94
Patrick, A. R., Reeves, J. N., Lobban, A. P., Porquet, D., & Markowitz,
A. G. 2011, MNRAS, 416, 2725
Reeves, J., Done, C., Pounds, K., Terashima, Y., Hayashida, K.,
Anabuki, N., Uchino, M., & Turner, M. 2008, MNRAS, 385, L108
Rivers, E., Markowitz, A., & Rothschild, R. 2011, ApJ, 732, 36
Ross, R. R., & Fabian A. C. 2005, MNRAS, 358, 211
Sambruna, R. M., Tombesi, F., Reeves, J. N., Braito, L., Ballo, L.,
Gliozzi, M., & Reynolds, C. S. 2011, ApJ, 734, 105
Schmoll, S., et al. 2009, ApJ, 703, 2171
Schurch, N. J., & Done, C. 2008, MNRAS, 386, L1
Smith, R. K., Brickhouse, N. S., Liedahl, D. A., & Raymond, J. C.
2001, ApJ, 556, L91
Takahashi, T., et al. 2007, PASJ, 59, S35
Titarchuk, L. 1994, ApJ, 434, 570
Yamada, S. 2011, PhD thesis, The University of Tokyo
Weaver, K. A., Mushotzky, R. F., Serlemitsos, P. J., Wilson, A. S.,
Elvis, M., & Briel, U. 1995, ApJ, 442, 597
Zoghbi, A., Fabian, A. C., Uttley, P., Miniutti, G., Gallo, L. C.,
Reynolds, C. S., Miller, J. M., & Ponti, G. 2010, MNRAS, 401,
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