Origin of the broad iron line feature and the soft X-ray variation in Seyfert galaxies

Naoki Iso,1,2,3 Ken Ebisawa,1,2,* Hiroaki Sameshima,1 Misaki Mizumoto,1,2 Takehiro Miyakawa,4 Hajime Inoue,1,5 and Hiroki Yamasaki1,2

1Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan
2Department of Astronomy, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
3Tokyo Seikoku University High School, 6-7-14 Oji, Kita-ku, Tokyo 114-0002, Japan
4Tsukuba Space Center (TKSC), Japan Aerospace Exploration Agency (JAXA), 2-1-1 Sengen, Tsukuba-shi, Ibaraki 305-8505, Japan
5Meisei University, 2-1-1 Hodokubo, Hino, Tokyo 191-8506, Japan

*E-mail: ebisawa@isas.jaxa.jp

Received 2015 December 7; Accepted 2016 January 29

Abstract

Many Seyfert galaxies are known to exhibit significant X-ray spectral variations and seemingly broad iron K-emission line features. In this paper, we show that the “variable partial covering model,” which has been successfully proposed for MCG −6–30–15 (Miyakawa et al. 2012, PASJ, 64, 140) and 1H 0707−495 (Mizumoto et al. 2014, PASJ, 66, 122), can also explain the spectral variations in 2–10 keV as well as the broad iron line features in 20 other Seyfert galaxies observed with Suzaku. In this model, the absorbed spectral component through the optically thick absorbing clouds has a significant iron K-edge, which primarily accounts for the observed, seemingly broad iron line feature. Fluctuation of the absorbing clouds in the line of sight of the extended X-ray source results in variation of the partial covering fraction, which causes an anti-correlation between the direct (not covered) spectral component and the absorbed (covered) spectral component below ∼10 keV. Observed spectral variation in 2–10 keV in a timescale of less than ∼1 day is primarily explained by such variations of the partial covering fraction, while the intrinsic soft X-ray luminosity is hardly variable.

Key words: accretion, accretion disks — galaxies: nuclei — galaxies: Seyfert — X-rays: galaxies

1 Introduction

Significant aperiodic X-ray variation is one of the main characteristics of active galactic nuclei (AGN). However, the origin of the AGN X-ray variation is not yet fully understood, in spite of extensive observational and theoretical studies (e.g., Mushotzky et al. 1993; Ulrich et al. 1997).

In particular, many Seyfert galaxies are known to exhibit an intriguing spectral variation in the iron K-energy band (6–7 keV). MCG −6–30–15 is a representative example of such Seyfert galaxies: its iron emission line profile seems to be broadened and skewed (e.g., Tanaka et al. 1995), and the fractional variation of the energy spectrum significantly drops at the iron line energy band (Fabian et al. 2002;
Matsumoto et al. 2003). A possible scenario to explain these phenomena is the “light-bending model.” In this model, the fluorescent iron line is emitted at the innermost part of the accretion disk, so that the line profile is broadened and skewed, and the disk-reflected photons are much less variable than the direct photons due to relativistic reverberation (Fabian & Vaughan 2003; Miniutti & Fabian 2004). Alternatively, the seemingly broad iron emission line feature may be due to an iron K-edge feature caused by partial covering of the central X-ray source by intervening absorbers in the line of sight (e.g., Matsuoka et al. 1990; Inoue & Matsumoto 2003; Miller et al. 2008). In this model, the apparent invariability of the iron energy band is explained as due to a relatively higher variation of the continuum caused by change in the amounts of absorption (Inoue & Matsumoto 2003).

Miyakawa, Ebisawa, and Inoue (2012, MEI2012 hereafter) proposed a “variable partial covering (VPC) model,” which is a sophistication of the latter idea. In this model, below ∼10 keV, the original X-ray luminosity of the AGN is not significantly variable, and the apparent X-ray variation is primarily caused by variation of the geometrical covering fraction of the extended X-ray source by the intervening clouds having internal ionization structures. MEI2012 applied the VPC model to Suzaku observations of MCG −6–30–15, and successfully explained not only the small fractional variation in the iron energy band, but also the spectral variations in 1–10 keV (see also Inoue et al. 2011), besides independent hard-tail variations above ∼10 keV. Mizumoto, Ebisawa, and Sameshima (2014, MES2014 hereafter) has shown that the VPC model can explain the soft X-ray spectral variations of the narrow Seyfert 1 galaxy 1H0707−405 observed with XMM and Suzaku below ∼10 keV. Therefore, it is interesting to examine whether the VPC model is valid for other Seyfert galaxies to explain the spectral variation below ∼10 keV and the broad iron emission line feature. In the present paper, we explore the Suzaku archive to select Seyfert galaxies that show similar X-ray spectral characteristics to MCG −6–30–15, and apply the VPC model to see if their X-ray spectral shapes and variations in 2–10 keV are explained by this model.

2 Observations and data reduction

2.1 Instruments

The data used in this paper were taken by Suzaku (Mitsuda et al. 2007), which has two operating instruments, the X-ray Imaging Spectrometer (XIS: Koyama et al. 2007) and the Hard X-ray Detector (HXD: Takahashi et al. 2007; Kokubun et al. 2007). The XIS is composed of four CCD cameras, XIS0 to XIS3, each of which is located on the focal plane of an identical X-ray telescope module (Serlemitsos et al. 2007). The XIS is sensitive in 0.2–12.0 keV, and the field of view (FOV) is 17.8 × 17.8. A half power diameter for the point spread function is ∼2′. XIS 0, 2, and 3 have front-illuminated (FI) chips, and XIS 1 has a back-illuminated (BI) one. Since the non-X-ray background (NXB) level of the FI CCDs is significantly lower than that of the BI CCD in the iron K-band, we use only the FI CCDs in the present study. The entire XIS 2 and part of XIS 0 have been non-functional since 2006 November and 2009 June, respectively, presumably due to micrometeorite hits. The available XIS FI cameras during each observation are shown in the last column of the observation log (table 1). The HXD consists of two types of detectors, PIN and GSO, achieving a combined sensitivity of 10–600 keV. We use only the PIN in this study (10–60 keV), since our targets are not bright enough to make a GSO spectral study feasible. The PIN has a FOV of ∼34′ square in FWHM.

2.2 Data selection

We chose data from the Suzaku public archive. Our main purpose is to study X-ray intensity and spectral variations of the Seyfert galaxies that have similar spectral characteristics to MCG −6–30–15, particularly in the iron K-energy band. Therefore, we selected only targets that are classified as Seyfert galaxies, and known to show a seemingly broad iron K-line feature, or a hint of one.

The unit of Suzaku observations is an observation “sequence,” which is a single continuous pointing period, typically for a day. For a given target, we combine the sequences carried out within a month to define a new “observation” (table 1). To study spectral variations efficiently, we chose only observations which satisfy the following conditions: (1) long enough total exposure time (>60 ks) for an observation, (2) bright enough that the total accumulated counts in an observation is more than 50000 counts in 0.2–10 keV, and (3) the sources are more variable than 10% in 4–10 keV in an observation. Thus, we selected 27 observations for 25 targets (using 50 sequences in total). The observation log is shown in table 1.

2.3 Data reduction

We reprocessed all the data under the standard pipeline version 2.5 and used HEAsoft1 version 6.11 for data reduction. For the XIS, we excluded events obtained during passages through the South Atlantic Anomaly (SAA) and from elevation angles <20° for the daytime Earth rim.

1 See (http://heasarc.nasa.gov/docs/software/heasoft/) for details.
| Observation # | Target                  | $\alpha$ (J2000.0) | $\delta$ (J2000.0) | $z$ | Sequence # | Start date | $t_{\text{exp}}$ (ks) | XIS |
|--------------|-------------------------|---------------------|---------------------|-----|------------|------------|----------------------|-----|
| 1            | Markarian 335           | 00:06:19.582        | $+20:12:10.58$      | 0.0254 | 701031010          | 2006-06-21             | 151 0 2 3                |
| 2            | TonS 180                | 00:57:19.940        | $-22:22:59.10$      | 0.0620 | 701021010          | 2006-12-09             | 120 0 3                  |
| 3            | 1H 0323+342             | 03:24:41.161        | $+34:10:45.86$      | 0.0629 | 704034010          | 2009-07-26             | 84 0 3                   |
| 4            | NGC 1365                | 03:33:36.310        | $-36:08:27.80$      | 0.0056 | 705031010          | 2010-06-27             | 151 0 3                  |
| 5            | 3C 111                  | 04:18:21.277        | $+38:01:35.80$      | 0.0485 | 704040010          | 2010-09-02             | 80 0 3                   |
| 6            | 1H 0419–577 (1)         | 04:26:00.715        | $-57:12:01.69$      | 0.1040 | 702041010          | 2007-07-25             | 205 0 3                  |
| 7            | 1H 0419–577 (2)         | —                   | —                   | —    | 704034010          | 2010-09-09             | 79 0 3                   |
| 8            | Arakelian 120           | 05:16:11.395        | $-00:08:59.65$      | 0.0323 | 702014010          | 2007-09-01             | 100 0 3                  |
| 9            | NGC 3227                | 10:23:30.608        | $+19:51:53.82$      | 0.0037 | 703022010          | 2008-10-28             | 58 0 3                   |
| 10           | NGC 3516                | 11:06:47.494        | $+72:34:06.70$      | 0.0088 | 704062010          | 2009-10-28             | 251 0 3                  |
| 11           | NGC 3783 (1)            | 11:39:01.721        | $-37:44:18.60$      | 0.0097 | 701033010          | 2006-06-24             | 75 0 3                   |
| 12           | NGC 3783 (2)            | —                   | —                   | —    | 704063010          | 2009-07-10             | 210 0 3                  |
| 13           | NGC 4051                | 12:03:09.686        | $+44:31:52.54$      | 0.0222 | 703023010          | 2008-11-06             | 274 0 3                  |
| 14           | NGC 4151                | 12:10:32.659        | $+39:24:20.74$      | 0.0033 | 701034010          | 2006-12-18             | 124 0 3                  |
| 15           | Markarian 766           | 12:18:26.484        | $+29:48:46.15$      | 0.0123 | 701035010          | 2006-11-16             | 98 0 3                   |
| 16           | Markarian 205           | 12:21:43.967        | $+75:18:37.99$      | 0.0708 | 705062010          | 2010-05-22             | 100 0 3                  |
| 17           | NGC 4593                | 12:39:39.492        | $-05:20:39.16$      | 0.0090 | 704000100          | 2007-12-15             | 118 0 3                  |
| 18           | IC 4329A                | 13:49:19.277        | $-30:18:33.83$      | 0.0160 | 702113010          | 2007-08-01             | 25 0 3                   |
| 19           | NGC 5548                | 14:17:59.513        | $+25:08:12.45$      | 0.0165 | 702042010          | 2006-06-18             | 31 0 3                   |
| 20           | 4C 74.26                | 20:42:37.285        | $+75:08:02.36$      | 0.1034 | 702057010          | 2007-10-28             | 91 0 3                   |
| 21           | Arakelian 564           | 22:42:39.309        | $+29:43:31.55$      | 0.0249 | 702117010          | 2007-06-26             | 99 0 3                   |
| 22           | SWIFT J2127.4+5654      | 21:27:45.400        | $+56:56:35.00$      | 0.0147 | 702122010          | 2007-12-09             | 91 0 3                   |
| 23           | NGC 7469                | 23:03:15.674        | $+08:52:25.28$      | 0.0159 | 703028010          | 2008-06-24             | 112 0 3                  |
| 24           | NGC 2992                | 09:45:42.045        | $-14:19:34.90$      | 0.0077 | 700005010          | 2005-11-06             | 37 0 2 3                 |
| 25           | MCG –5–23–16           | 09:47:40.170        | $-30:56:55.91$      | 0.0082 | 700020100          | 2005-12-07             | 95 0 2 3                 |
| 26           | Centaurus A             | 13:25:27.615        | $-43:01:08.81$      | 0.0018 | 704108010          | 2009-07-20             | 62 0 3                   |
| 27           | IRAS 18325–5926         | 18:36:58.257        | $-59:24:08.44$      | 0.0194 | 702118010          | 2007-10-26             | 78 0 3                   |
Fig. 1. XIS light curves of the 27 observations in 0.2–12.0 keV. The count rate is binned with 512 s. Horizontal dotted lines show the count-rate intervals with which the intensity-sliced spectra were made (subsection 3.2). Vertical dotted lines show the time intervals with which the time-sliced spectra were made (subsection 3.3). (Color online)

and $<5^\circ$ for the night Earth rim. The source events were extracted from regions within a $3'$ radius of the source. The background events were extracted from an annulus of radii $4'-6'$ when the source is located at the XIS nominal position, or from regions within a $3'$ radius of the position offset from the source avoiding the calibration source at chip corners when the source is located at the HXD nominal position. Figure 1 shows the 0.2–12.0 keV light curves with XIS for all 27 observations. As for the spectral analysis, we used redistribution matrix files.
(RMFs) and ancillary response files (ARFs), generated by the \texttt{xisrmfgen} and \texttt{xissimarfgen} (Ishisaki et al. 2007) tools. Three or two XIS FI spectra and responses were combined.

For the HXD/PIN, we exclude events obtained during passages through the SAA and from elevation angles <5° for dark Earth rim. The PIN background is composed of the non-X-ray background (NXB) and the cosmic X-ray...
background (CXB). We simulated background data for the spectral analysis. The NXB spectrum was provided by the instrument team (Fukazawa et al. 2009), while the CXB spectrum was simulated by convolving the HEAO-1 model (Boldt 1987) with the detector response.

3 Data analysis and results

3.1 Time-averaged spectra

Since we are primarily interested in the iron K-line band, we use only 2–10 keV of the XIS data for spectral fitting, to
avoid complexities in the softer (<2 keV) energy band. We also use the PIN data in 10–40 keV, which help to constrain the underlying continuum to study the iron K-band feature.

First, we analyze the time-averaged spectra of the 27 observations from the 25 sources. We apply the same “three-component model” proposed by MEI2012. The model is represented as

\[ F = W_H W_L (N_1 + W_2 N_2) P + RPN_3 + I_{Fe}, \] (1)

where \( P \) is the intrinsic cut-off power-law spectrum; \( N_1 \) and \( N_2 \) are the direct power-law normalization and the absorbed power-law normalization, respectively. \( W_H, W_L, \) and \( W_2 \) represent the transmissions due to high-ionized warm absorber, low-ionized warm absorber, and partial heavy absorber \( (N_{HI} \gtrsim 10^{24} \text{cm}^{-2}) \), respectively. Each warm absorber has two parameters, the hydrogen column density, \( N_{HI} \), and the ionization parameter, \( \xi \): such that \( W_H = \exp[-\sigma(\xi_H)N_{HI}], W_L = \exp[-\sigma(\xi_L)N_{IL}], \) and \( W_2 = \exp[-\sigma(\xi_2)N_{II}], \) where \( \sigma(\xi) \) means the energy-dependent photo-absorption cross-section at \( \xi \). \( R \) and \( N_3 \) are the reflection albedo and the reflection normalization by the neutral accretion disk, respectively (so that \( RPN_3 \) is the disk reflection component), and \( I_{Fe} \) is a narrow iron Kα emission line. The interstellar extinction is also included in the model fitting, but is not explicitly shown in equation (1).

We used the X-ray spectral fitting package XSPEC version 12.7.0 for the spectral analysis. For the interstellar absorption and the disk reflection, we adopted \texttt{phabs} and \texttt{pexrav} (Magdziarz & Zdziarski 1995) in XSPEC. Following MEI2012, the cut-off energy and the disk inclination angle are fixed at 160 keV and 30°, respectively. \( N_3 \) is linked to \( N_1 \) so that \( N_3/N_1 \sim \Omega/2\pi = 0.3 \), where \( \Omega \) is the solid angle of the disk seen from the central source; we confirmed that changing the inclination angle only slightly changes the best-fitting spectral parameters within statistical errors. For the warm absorbers, we use the table-grid model calculated by MEI2012 using XSTAR (version 2.1kn8), where the redshift was fixed at 0.001.

In the following, we set the acceptance criterion of a successful model fit as a reduced \( \chi^2 < 1.2 \).

Four sources did not satisfy the criterion: NGC 1365 (reduced \( \chi^2 = 1.48 \)), NGC 3227 (1.23), NGC 4151 (1.24), and Centaurus A (1.42). 3C 111 satisfied the fitting criterion (reduced \( \chi^2 = 1.01 \)), but the heavily absorbed component \( (W_2N_2) \) was not required. Since the heavily absorbed component is the most important player in our VPC model to produce the broad iron line feature and the spectral variation below \( \sim 10 \) keV, we drop 3C 111 from further study.

Consequently, 22 observations out of 20 sources are successfully represented with the three-component model (figure 2), and used for further study. The best-fitting parameters of the 22 time-averaged spectra are summarized in table 2.
Fig. 2. Background-subtracted time-averaged XIS and PIN spectra. The data and the best-fitting model are in the upper panel, while the residuals are in the lower panel. (Color online)

In the case of MCG$-6\text{d}30\text{d}-15$, all the high-ionized absorber ($W_{\text{H}}$), low-ionized absorber ($W_{\text{L}}$), and the heavy absorber ($W_{\text{H}}$) were required (MEI2012). However, we found the three absorbers are not always necessary. In fact, only one of the 22 spectra requires all three absorbers (we call this “Group A”). In addition to the heavy absorber, seven spectra require only the high-ionized absorber (Group B), and one requires only the low-ionized absorber (Group C).
Fig. 2. (Continued) (Color online)

absorber (Group C). Thirteen require none besides the heavy absorber (Group D). We accept these differences as a diversity of Seyfert galaxies, for the time being, not being able to find an obvious reason to explain the difference. Our models for Groups A, B, C, and D are illustrated in figure 3.

3.2 Intensity-sliced spectra

Next, we study spectral variations during each of the 22 observations (out of 20 sources), and we successfully fitted the three-component model to their averaged spectra. We examine whether or not the VPC model
proposed by MEI2012 explains the observed spectral variations.

3.2.1 Model
To prepare, we briefly review the VPC model. Let us define the “total normalization,” \( N \), and the partial covering fraction, \( \alpha \), so that

\[
N = N_1 + N_2, \tag{2}
\]

and

\[
N_1 = (1 - \alpha)N, \quad N_2 = \alpha N. \tag{3}
\]

Here, we consider a situation such that the total normalization, \( N \), represents the intrinsic AGN luminosity, and the X-ray source, having a finite size, is partially covered by fragmented heavy absorbing clouds (with absorption \( W_2 \)), where the geometrical, partial covering fraction is \( \alpha \).

Detailed study of spectral variations of MCG–6–30–15 by MEI2012 revealed, surprisingly, that the low-ionized warm absorption \( W_L = \exp \left\{-\sigma(\xi_L)N_{H,L}\right\} \) is related to the same partial covering fraction \( \alpha \), such that

\[
N_{H,L} = \alpha \langle N_{H,L} \rangle, \tag{4}
\]

where \( \langle N_{H,L} \rangle \) is the common amount of the column density of the low-ionized absorber while the spectra vary. This relation was unexpected, since the low-ionized absorption \( W_L \) and the partial covering fraction due to \( W_2 \) should, in principle, be independent [see equation (1)]. MEI2012 interpreted this relation as that the low-ionized absorber \( (W_L) \) and the heavy absorber \( (W_2) \) are parts of the same
Table 2. Best-fitting parameters for time-averaged spectra.*

| (1) Target       | (2) N_{H,1SM} \pm 0.12 | (3) N_{H,1} log $\xi_1$ | (4) N_{H,2} log $\xi_1$ | (5) N_1 | (6) N_2 | (7) N_{H,2} log $\xi_2$ | (8) $\Gamma$ | (9) $E_{Fe}$ | (10) EW_{Fe} | (11) $I_{Fe}$ | (12) Re-$\chi^2$ (d.o.f.) |
|------------------|--------------------------|--------------------------|--------------------------|--------|--------|--------------------------|-------------|-------------|----------------|-------------|---------------------|
| Markarian 335    | 0.28$^{+0.15}_{-0.17}$   | <0.01                    | <0.1                     | 7.77$^{+0.51}_{-0.55}$ | 7.66$^{+2.54}_{-2.06}$ | 1.79$^{+0.34}_{-0.35}$ | 2.24$^{+0.04}_{-0.05}$ | 6.21$^{+0.02}_{-0.03}$ | 0.64$^{+0.14}_{-0.14}$ | 1.07          |
| TonS 180         | <0.01                    | <0.01                    | <0.1                     | 3.53$^{+0.13}_{-0.13}$ | 9.86$^{+4.43}_{-4.11}$ | 4.51$^{+4.86}_{-1.85}$ | 2.35$^{+0.03}_{-0.03}$ | 6.16$^{(6w)}_{(6w)}$ | 0.08$^{+0.10}_{-0.08}$ | 1.02          |
| IH 0323+342      | <0.01                    | <0.01                    | <0.1                     | 3.32$^{+0.14}_{-0.14}$ | 1.44$^{+0.95}_{-0.87}$ | 1.81$^{+2.81}_{-1.44}$ | 1.90$^{+0.04}_{-0.04}$ | 6.40$^{(6w)}_{(6w)}$ | 0.01$^{+0.18}_{-0.01}$ | 0.93          |
| IH 0419–577 (1)  | <0.01                    | 0.23$^{+0.60}_{-0.18}$   | <0.1                     | 5.15$^{+0.11}_{-0.04}$ | 3.00$^{+0.73}_{-0.67}$ | 2.15$^{+0.35}_{-0.17}$ | 1.86$^{+0.02}_{-0.01}$ | 5.79$^{+0.06}_{-0.05}$ | 0.21$^{+0.13}_{-0.13}$ | 1.06          |
| IH 0419–577 (2)  | <0.01                    | 3.47$^{+0.44}_{-0.24}$   | <0.1                     | 4.01$^{+0.11}_{-0.12}$ | 1.17$^{+0.68}_{-0.54}$ | 1.92$^{+1.68}_{-0.52}$ | 1.83$^{+0.03}_{-0.03}$ | 5.79$^{+0.03}_{-0.03}$ | 0.41$^{+0.18}_{-0.18}$ | 1.07          |
| Arakelian 120    | <0.01                    | <0.01                    | <0.1                     | 11.29$^{+0.36}_{-0.23}$ | 7.90$^{+1.76}_{-1.20}$ | 2.74$^{+1.18}_{-1.08}$ | 2.02$^{+0.03}_{-0.01}$ | 6.20$^{+0.02}_{-0.01}$ | 1.86$^{+0.29}_{-0.27}$ | 0.90          |
| NGC 3516         | 1.32$^{+0.16}_{-0.09}$   | 2.64$^{+8.67}_{-1.33}$   | <0.1                     | 3.17$^{+0.20}_{-0.21}$ | 2.17$^{+0.64}_{-0.58}$ | 1.55$^{+0.27}_{-0.19}$ | 1.69$^{+0.04}_{-0.05}$ | 6.34$^{+0.00}_{-0.00}$ | 3.66$^{+0.17}_{-0.17}$ | 0.98          |
| NGC 3783 (1)     | 0.93$^{+0.22}_{-0.13}$   | 0.13$^{+0.19}_{-0.05}$   | <0.1                     | 11.10$^{+0.99}_{-0.53}$ | 3.80$^{+2.20}_{-0.87}$ | 1.31$^{+0.32}_{-0.36}$ | 1.70$^{+0.06}_{-0.05}$ | 6.33$^{+0.01}_{-0.01}$ | 6.34$^{+0.36}_{-0.37}$ | 0.98          |
| NGC 3783 (2)     | 0.27$^{+0.44}_{-0.27}$   | 0.33$^{+0.23}_{-0.15}$   | <0.1                     | 2.51$^{+0.22}_{-0.05}$ | 5.82$^{+1.65}_{-1.30}$ | 1.74$^{+0.85}_{-0.27}$ | 1.74$^{+0.03}_{-0.03}$ | 6.32$^{+0.01}_{-0.00}$ | 6.10$^{+0.41}_{-0.34}$ | 1.08          |
| NGC 4051         | <0.01                    | 0.07$^{+0.11}_{-0.05}$   | <0.1                     | 8.69$^{+0.10}_{-0.04}$ | 6.93$^{+0.80}_{-0.90}$ | 2.34$^{+0.71}_{-0.37}$ | 2.00$^{+0.01}_{-0.01}$ | 6.39$^{+0.01}_{-0.01}$ | 1.50$^{+0.13}_{-0.13}$ | 1.11          |
| Markarian 205    | 0.33$^{+0.31}_{-0.33}$   | <0.01                    | <0.1                     | 3.40$^{+0.86}_{-0.46}$ | 6.55$^{+3.21}_{-2.44}$ | 5.11$^{+1.54}_{-0.41}$ | 1.98$^{+0.09}_{-0.10}$ | 5.97$^{+0.03}_{-0.03}$ | 0.71$^{+0.18}_{-0.18}$ | 1.05          |
| Markarian 766    | 0.18$^{+0.45}_{-0.18}$   | <0.01                    | <0.1                     | 2.66$^{+2.36}_{-2.66}$ | 6.70$^{+0.85}_{-0.35}$ | 5.08$^{+2.55}_{-2.09}$ | 2.15$^{+2.32}_{-0.66}$ | 2.16$^{+0.07}_{-0.09}$ | 6.39$^{+0.02}_{-0.03}$ | 1.06$^{+0.39}_{-0.33}$ | 1.02          |
| Target          | \(N_{\text{H,SM}}\) | \(N_{\text{H,H}}\) | \(N_{\text{H,L}}\) | \(N_1\) | \(N_2\) | \(N_{\text{H,2}}\) | \(\xi\) | \(E_{\text{Fe}}\) | \(I_{\text{Fe}}\) | \(\chi^2\) (d.o.f) |
|-----------------|----------------------|-------------------|-------------------|--------|--------|-------------------|--------|----------------|----------------|-------------------|
| NGC 4593        | 0.43\(\pm\)0.17     | <0.01             | <0.1              | 2.44\(\pm\)0.25 | 1.60\(\pm\)0.30 | 1.80\(\pm\)0.17 | 1.75\(\pm\)0.17 | 6.35\(\pm\)0.17 | 2.56\(\pm\)0.17 | 1.04   |
| IC 4329A        | 0.61\(\pm\)0.09     | <0.01             | <0.1              | 32.84\(\pm\)0.47 | 12.35\(\pm\)1.90 | 1.62\(\pm\)0.27 | 1.85\(\pm\)0.04 | 6.29\(\pm\)0.04 | 5.62\(\pm\)0.44 | 1.01   |
| NGC 5548        | 0.41\(\pm\)0.05     | 0.13\(\pm\)0.07   | <0.1              | 4.25\(\pm\)0.25 | 1.43\(\pm\)0.27 | 1.63\(\pm\)0.32 | 1.78\(\pm\)0.14 | 5.81\(\pm\)0.03 | 3.23\(\pm\)0.31 | 1.05   |
| 4C 74.26        | 0.59\(\pm\)0.18     | <0.01             | <0.1              | 11.75\(\pm\)0.95 | 5.03\(\pm\)2.70  | 2.72\(\pm\)0.61 | 1.98\(\pm\)0.05 | 6.43\(\pm\)0.06 | 0.28\(\pm\)0.21 | 0.98   |
| Arakelian 564   | 0.22\(\pm\)0.22     | 0.44\(\pm\)1.16   | <0.1              | 16.71\(\pm\)1.16 | 23.51\(\pm\)6.38 | 2.78\(\pm\)1.42 | 2.60\(\pm\)0.07 | 1.64\(\pm\)0.37 | 0.98\(\pm\)0.44 | 0.94   |
| SWIFT J2127.4   | 1.57\(\pm\)0.24     | <0.01             | <0.1              | 17.13\(\pm\)1.70 | 12.13\(\pm\)6.06 | 1.66\(\pm\)0.37 | 2.17\(\pm\)0.07 | 6.28\(\pm\)0.04 | 0.98\(\pm\)0.44 | 0.94   |
| NGC 7469        | 0.22\(\pm\)0.16     | 0.07\(\pm\)0.37   | <0.1              | 5.94\(\pm\)0.34 | 3.08\(\pm\)1.35  | 1.64\(\pm\)0.66 | 1.84\(\pm\)0.03 | 6.27\(\pm\)0.01 | 2.47\(\pm\)0.25 | 0.93   |
| NGC 2992        | 1.84\(\pm\)0.24     | <0.01             | <0.1              | 3.34\(\pm\)0.32 | 1.80\(\pm\)0.66  | 1.30\(\pm\)0.48 | 1.80\(\pm\)0.07 | 6.34\(\pm\)0.01 | 3.11\(\pm\)0.17 | 1.05   |
| MCG-5-23-16     | 2.40\(\pm\)0.06     | <0.01             | <0.1              | 29.65\(\pm\)0.68 | 11.08\(\pm\)1.46 | 1.50\(\pm\)0.14 | 1.86\(\pm\)0.01 | 6.33\(\pm\)0.01 | 3.73\(\pm\)0.42 | 1.08   |
| IRAS 18325      | 2.48\(\pm\)0.21     | <0.01             | <0.1              | 19.83\(\pm\)1.32 | 10.35\(\pm\)4.37 | 1.57\(\pm\)0.30 | 2.41\(\pm\)0.06 | 6.28\(\pm\)0.03 | 0.80\(\pm\)0.30 | 1.02   |

*Errors correspond to 90% confidence limits. The table columns are as follows: (1) Target name; (2) Hydrogen column density of the interstellar matter \((10^{22}\ \text{cm}^{-2})\); (3) Hydrogen column density \((10^{23}\ \text{cm}^{-2})\) and logarithm of the ionization parameter for \(W_2\); (4) Hydrogen column density \((10^{22}\ \text{cm}^{-2})\) and logarithm of the ionization parameter for \(W_1\); (5) Normalization of the direct component \((10^{-3}\ \text{photons} \ \text{s}^{-1} \ \text{cm}^{-2} \ \text{keV}^{-1}\) at 1\text{keV})); (6) Normalization of the absorbed component \((10^{-7}\ \text{photons} \ \text{s}^{-1} \ \text{cm}^{-2} \ \text{keV}^{-1}\) at 1\text{keV})); (7) Hydrogen column density \((10^{24}\ \text{cm}^{-2})\) and logarithm of the ionization parameter for \(W_2\); (8) Photon index of the power-law component; (9) Iron line energy (keV), intensity \((10^{-3}\ \text{photons} \ \text{s}^{-1} \ \text{cm}^{-2})\) and equivalent width (eV); (10) Reduced \(\chi^2\) and the degree of freedom.
Fig. 3. Model for the four groups of spectra we analyzed. Group A requires all three absorbers: the heavy partial absorber as the core of the absorbing clouds, the low-ionized absorber as an envelope of the clouds, and the uniformly surrounding high-ionized absorber. Group B requires the partial heavy absorber and the high-ionized absorber. Group C requires the partial heavy absorber and the low-ionized absorber. Group D requires only the partial heavy absorber. (Color online)

absorbing clouds (figure 3), so that a “double partial covering” with the same covering fraction is presumably the case (MES2014).

Consequently, the three-component model in equation (1) is rewritten as

\[
F = \exp \left[ -\sigma(\xi_H) N_{H,1} \right] \exp \left[ -\sigma(\xi_L) \alpha N_{H,1} \right] \\
\times \left[ 1 - \alpha + \alpha \exp \left[ -\sigma(\xi_2) N_{H,2} \right] \right] PN \\
+ RP N_3 + I_{Fe}. \tag{5}
\]

MEI2012 applied this model to the eight intensity-sliced spectra of MCG−6–30–15 observed with Suzaku, where the good time intervals (GTIs) are determined using XIS below 10 keV. \(N_3\) is assumed to be constant, and fixed at 0.3 time the average of \(N_1 = (1 - \alpha)N\). The iron line parameters are also fixed at those obtained from the time-averaged spectra. These spectra were explained well in 1–40 keV by only variation of \(\alpha\), whereas \(N\) does not vary apart from the brightest one (where \(N\) is 1.5 times greater); all the other spectral parameters do not vary (= common to all the variable spectra).

### 3.2.2 Model fitting

Following MEI2012, we create the intensity-sliced spectra based on the XIS flux, and examine the VPC model in equation (5). For each observation, we define four intensity ranges in the 0.2–12.0 keV light curve so that the photon counts for each intensity range will be approximately equal, and create the four intensity-sliced energy spectra. The dotted horizontal lines in figure 1 indicate the intensity boundaries for each observation.

We try to fit the four intensity-sliced spectra in 2–40 keV simultaneously with equation (5), making only \(\alpha\) variable. If necessary, \(N\) is varied in addition. The other parameters are common to all four spectra, and the best-fitting values are determined from the model fitting (table 3).

As a result, we successfully fitted the intensity-sliced spectra of the 20 observations of 18 sources only varying \(\alpha\). The two remaining sources (Markarian 766 and NGC 5548) require \(N\) to be slightly variable: Markarian 766 requires \(N\) for the brightest spectrum to be \(\sim 1.3\) times greater than the rest. NGC 5548 requires the \(N\) for the two brighter spectra to be \(\sim 1.7\) times higher than the two dimmer. We summarize the spectral fitting results...
| Target          | $N_{H, ISM}$ | $N_{HI}$ | $N$ | $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $\alpha_4$ | $\log \xi_1$ | $\log \xi_2$ | $\log \xi_3$ | $\log \xi_4$ | $\chi^2$ | $\Delta \chi^2$ | $\Delta \nu$ |
|----------------|-------------|----------|-----|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|----------|----------------|-------------|
| Markarian 335  | 0.20$^{+0.08}_{-0.08}$ | <0.01    | 1.48| 0.61$^{+0.11}_{-0.09}$ | 0.53$^{+0.13}_{-0.11}$ | 0.46$^{+0.16}_{-0.12}$ | 0.35$^{+0.19}_{-0.14}$ | <0.1        | 1.79        | 2.19$^{+0.02}_{-0.01}$ | 1.03        | 1709     |                |              |
| TonS 180       | <0.01       | <0.01    | 1.33| 0.78$^{+0.08}_{-0.08}$ | 0.74$^{+0.09}_{-0.09}$ | 0.73$^{+0.10}_{-0.10}$ | 0.67$^{+0.12}_{-0.12}$ | <0.1        | 4.51        | 2.33$^{+0.03}_{-0.03}$ | 0.90        | 476      |                |              |
| 1H 0323+342    | <0.01       | <0.01    | 0.51| 0.46$^{+0.09}_{-0.10}$ | 0.37$^{+0.11}_{-0.10}$ | 0.31$^{+0.12}_{-0.12}$ | 0.26$^{+0.13}_{-0.13}$ | <0.1        | 1.81        | 1.89$^{+0.02}_{-0.01}$ | 0.97        | 1357     |                |              |
| 1H 0419–577 (1)| <0.01       | 0.23     | 0.80| 0.44$^{+0.04}_{-0.03}$ | 0.38$^{+0.05}_{-0.06}$ | 0.32$^{+0.05}_{-0.08}$ | 0.27$^{+0.06}_{-0.08}$ | <0.1        | 2.15        | 1.86$^{+0.01}_{-0.01}$ | 1.01        | 1877     |                |              |
| 1H 0419–577 (2)| <0.01       | <0.01    | 0.53| 0.31$^{+0.09}_{-0.13}$ | 0.26$^{+0.08}_{-0.11}$ | 0.21$^{+0.09}_{-0.12}$ | 0.19$^{+0.12}_{-0.13}$ | <0.1        | 1.92        | 1.83$^{+0.01}_{-0.01}$ | 1.07        | 867      |                |              |
| Arakelian 120  | <0.01       | <0.01    | 1.90| 0.48$^{+0.08}_{-0.08}$ | 0.44$^{+0.09}_{-0.09}$ | 0.38$^{+0.10}_{-0.10}$ | 0.33$^{+0.11}_{-0.11}$ | <0.1        | 2.74        | 2.01$^{+0.01}_{-0.01}$ | 1.00        | 1383     |                |              |
| NGC 3783 (1)   | 1.09$^{+0.07}_{-0.07}$ | 0.13     | 1.69| 0.39$^{+0.09}_{-0.09}$ | 0.33$^{+0.10}_{-0.10}$ | 0.28$^{+0.11}_{-0.11}$ | 0.19$^{+0.13}_{-0.13}$ | <0.1        | 1.31        | 1.73$^{+0.01}_{-0.01}$ | 1.05        | 2447     |                |              |
| NGC 3783 (2)   | 1.30$^{+0.06}_{-0.14}$ | 0.33     | 2.10| 0.36$^{+0.07}_{-0.09}$ | 0.26$^{+0.07}_{-0.07}$ | 0.20$^{+0.08}_{-0.11}$ | 0.14$^{+0.08}_{-0.09}$ | 3.39        | 1.74        | 1.72$^{+0.01}_{-0.01}$ | 1.04        | 4417     |                |              |
| NGC 3516       | 1.45$^{+0.06}_{-0.08}$ | 2.64     | 0.58| 0.64$^{+0.02}_{-0.08}$ | 0.42$^{+0.07}_{-0.07}$ | 0.32$^{+0.07}_{-0.07}$ | 0.19$^{+0.07}_{-0.07}$ | <0.1        | 1.55        | 1.70$^{+0.01}_{-0.01}$ | 1.12        | 1448     |                |              |
| NGC 4051       | <0.01       | 0.07     | 1.55| 0.66$^{+0.03}_{-0.01}$ | 0.47$^{+0.09}_{-0.04}$ | 0.32$^{+0.15}_{-0.10}$ | 0.08$^{+0.28}_{-0.07}$ | <0.1        | 2.34        | 2.00$^{+0.01}_{-0.01}$ | 1.10        | 4870     |                |              |
### Table 3. (Continued)

| Target          | N*ISM | N_{H,H} | \log \xi_{H} | a_1 | (N_{H,L}) | N_{H,2} | \log \xi_{2} | a_2 | a_3 | a_4 | \Gamma | Re-\chi^2 (d.o.f) |
|-----------------|-------|---------|---------------|-----|-----------|---------|--------------|-----|-----|-----|--------|------------------|
| Markarian 205   | 0.26^{+0.17}_{-0.16} | <0.01 | 0.92 | 0.6^{+0.16}_{-0.15} | <0.1 | 5.11 | 1.9^{+0.02}_{-0.02} | 1.21 | (479) |
| Markarian 766   | 0.10^{+0.19}_{-0.09} | <0.01 | 1.12 | 0.62^{+0.15}_{-0.14} | 7.59 | 2.15 | 2.15^{+0.02}_{-0.01} | 1.08 | (812) |
| NGC 4593        | 0.46^{+0.10}_{-0.14} | <0.01 | 0.43 | 0.57^{+0.07}_{-0.13} | <0.1 | 1.80 | 1.72^{+0.02}_{-0.01} | 0.97 | (699) |
| IC 4329A        | 0.61^{+0.02}_{-0.03} | <0.01 | 4.40 | 0.45^{+0.03}_{-0.02} | <0.1 | 1.62 | 1.84^{+0.00}_{-0.00} | 1.04 | (6262) |
| NGC 5548        | 0.62^{+0.05}_{-0.05} | 0.13 | 2.94^{+0.16}_{-0.05} | 1.00 | 0.55^{+0.04}_{-0.03} | <0.1 | 1.63 | 1.70^{+0.01}_{-0.01} | 1.00 | (3024) |
| 4C 74.26        | 0.61^{+0.09}_{-0.09} | <0.01 | 1.70 | 0.35^{+0.16}_{-0.16} | <0.1 | 2.72 | 1.98^{+0.01}_{-0.01} | 1.03 | (1272) |
| Arakelian 564   | 0.09^{+0.06}_{-0.09} | 0.44 | 3.46^{+0.27}_{-0.27} | 3.88 | 0.69^{+0.14}_{-0.16} | <0.1 | 2.78 | 2.55^{+0.02}_{-0.01} | 1.05 | (969) |
| SWIFT J2127.4   | 1.50^{+0.11}_{-0.11} | <0.01 | 2.54 | 0.48^{+0.16}_{-0.14} | <0.1 | 1.66 | 2.13^{+0.02}_{-0.01} | 1.00 | (783) |
| NGC 7469        | 0.23^{+0.08}_{-0.09} | 0.07 | 3.02^{+0.38}_{-0.23} | 0.91 | 0.48^{+0.06}_{-0.07} | <0.1 | 1.64 | 1.83^{+0.01}_{-0.01} | 0.93 | (1076) |
| NGC 2992        | 1.71^{+0.06}_{-0.14} | <0.01 | 0.46 | 0.6^{+0.10}_{-0.15} | <0.1 | 1.30 | 1.73^{+0.01}_{-0.01} | 1.03 | (1660) |
### 3.3 Time-sliced spectra

Next, we see if the time sequences of the soft X-ray energy spectra are also explained by the VPC model with time-varying partial covering fractions. In the XIS light curves, we define boundaries of the time-sliced spectra every $2.3 \times 10^4$ s, which corresponds to four Suzaku orbital periods. The vertical dotted lines in figure 1 show the time boundaries for each observation, and we made energy spectra from each time bin. The numbers of time-sliced spectra in a single observation are from 6 (4C 74.26) to 28 (NGC 4051). For each observation, a time series of the XIS and PIN spectra are fitted simultaneously with the VPC model in equation (5), while spectral variation above 10 keV is hardly constrained, because the photon statistic is not sufficient. We first try to fit the spectra only allowing the partial covering fraction $\alpha$ to vary. If not successful (i.e., $\chi^2 > 1.2$), the total normalization $N$ is also varied.

As a result, we found that the XIS spectral variations are explained by only varying $\alpha$ for 21 observations from among 19 sources. Figure 5 shows the variation of the observed counting rates in 0.2–12 keV and the partial covering fraction for each of the 21 observations. An anti-correlation between the counting rate and the partial covering fraction is obvious. Namely, apparent soft X-ray flux and spectral variations below $\sim 10$ keV are primarily caused by variation of the partial covering fraction. Only the remaining source, NGC 5548, needs the total normalization $N$ varying in addition to $\alpha$ within a single observation. Figure 6 shows the variation of the counting rates and partial covering fraction for NGC 5548. Note that the observation of NGC 5548 spans more than $4 \times 10^6$ s, which is the longest in our samples, and the total normalization $N$ is still constant on timescales less than several $10^5$ s. This suggests that the intrinsic luminosity variation of Seyfert galaxies has a timescale longer than $\sim 10^5$ s.

#### 3.4 Variation in the iron line energy band

In order to study a variation in the iron line energy band, we calculate the root mean square (RMS) spectra for the 22 observations. We use the same time series of spectra used in the previous subsection. Namely, RMS spectra are calculated with a bin width of $2.3 \times 10^4$ s.

For a time series of $\{x_i \pm \delta x_i \}_{i=1}^N$, where $\{x_i\}$ are background-subtracted counting rates, $\{\delta x_i\}$ are their errors, and $N$ is the number of the time-bins, the RMS variability is given as

$$
\text{RMS variability} = F_{\text{var}} = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (x_i - \bar{x})^2 - \frac{1}{N} \sum_{i=1}^{N} \delta x_i^2 / \bar{x}}.
$$

where $\bar{x} = (\sum_{i=1}^{N} x_i) / N$, and the error is

$$
\text{RMS error} = \frac{1}{F_{\text{var}}} \sqrt{\frac{1}{2N} \left[ \frac{1}{N-1} \sum_{i=1}^{N} (x_i - \bar{x})^2 / \bar{x}^2 \right]},
$$

### Table 3. (Continued)

| Target       | $N_{\text{H,ISM}}$ | log $\xi_{\text{H}}$ | $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $\alpha_4$ |
|--------------|---------------------|-----------------------|----------------|----------------|----------------|----------------|
| MCG −5−23−16 | 2.40±0.02           | <0.01                 | 4.11           | 0.42±0.03     | <0.00          | 1.09           |
| IRAS 18325   | 2.54±0.08           | <0.01                 | 3.19           | 0.57±0.04     | <0.00          | 1.09           |

$^a$Errors correspond to 90% confidence limits. The table columns are as follows: (1) Target name; (2) Hydrogen column density of the interstellar matter ($10^{22}$ cm$^{-2}$); (3) Hydrogen column density ($10^{23}$ cm$^{-2}$) and logarithm of the ionization parameter for $W_1$; (4) Normalization of the power-law component ($10^{-3}$ photons s$^{-1}$ cm$^{-2}$ keV$^{-1}$) at 1 keV; (5) Four partial covering fractions corresponding to the four intensity-sliced spectra; (6) Common hydrogen column density ($10^{23}$ cm$^{-2}$) of the low-ionized absorber and logarithm of the ionization parameter for $W_1$; (7) Hydrogen column density ($10^{24}$ cm$^{-2}$) and logarithm of the ionization parameter for $W_2$; (8) Photon index of the power-law component; (9) Reduced $\chi^2$ and the degree of freedom.
Fig. 4. Model fitting results of the intensity-sliced XIS and PIN spectra. For each observation, the four intensity-sliced spectra are made using XIS with approximately equal counts for each intensity range, and the same GTIs are used to extract PIN spectra. The four spectra are fitted simultaneously by varying only the partial covering fraction, $\alpha$, except for Markarian 766 and NGC 5548 where $N$ is also slightly varied (see text). The data and the best-fitting power-law model are in the upper panel, while the residuals are in the lower panel. (Color online)
(Edelson et al. 2002). For each observation, we computed the RMS variability for 15 energy bands with equation (6) to constitute the RMS spectrum. We used only the XIS data in 2–10 keV to focus on the iron line energy band. The 22 RMS spectra are shown in figure 7 (in black).

Since each time-sliced spectrum is fitted successfully with the VPC model, the RMS model spectra can be calculated from the best-fitting VPC model spectra. These model RMS spectra are also shown in figure 7 (in red). We find that the observed RMS spectra and the model RMS spectra...
Fig. 4. (Continued) (Color online)

agree well, and both tend to show drops at the iron line energy band (6–7 keV). The reason for that is discussed in subsection 4.1.

4 Discussion

4.1 Origin of the broad iron line feature and the soft X-ray variation

We have seen that the variable partial covering (VPC) model, which has been proposed for MCG−6−30−15 (MEI2012) and 1H 0707−495 (MES2014), can explain the 2–10 keV spectral variation of the 20 other Seyfert galaxies observed with Suzaku. The original VPC model for MCG−6−30−15 requires three types of absorbers: optically thick partial absorbing clouds, optically thin envelopes of clouds, and a uniformly surrounding highly ionized absorber (Group A in figure 3). 1H 0707−495 does not require the highly ionized absorber (Group C in figure 3; MES2014), and the 20 targets studied in this paper are grouped into four depending on the number and types of the absorbers required (figure 3). The optically thick partial absorbers are always required, where the hydrogen column densities are \( \gtrsim 10^{24} \) cm\(^{-2}\) and the partial covering fraction is variable from \( \sim 0.1 \) to \( \sim 0.7 \) (table 3).

The heavily absorbed spectral components by such optically thick absorbing clouds exhibit a strong iron K-edge, which, together with the distant reflection feature (narrow iron emission line and weak iron K-edge), can explain the observed spectral feature in the iron K-band (figure 2). Because such thick absorbers are completely opaque at \( \sim 2 \) keV (figure 2), a variation of the partial covering
fraction can cause significant soft X-ray flux variations even if the intrinsic X-ray luminosity is constant. In fact, the observed flux and spectral variations below $\sim 10$ keV on a timescale of $\lesssim 1$ day are explained by a variation of only the partial covering fraction, while the intrinsic luminosity below $\sim 10$ keV is assumed to be constant (figures 4 and 5).

It is well known that the fractional variation at the broad iron line-like feature in MCG$-$6$-$30$-$15 is significantly

Fig. 5. Variations of the observed XIS counting rates (0.2–12 keV; black, scale at left) and the partial covering fractions (red, scale at right) for 21 observations.
reduced (Fabian et al. 2002; Matsumoto et al. 2003; Inoue & Matsumoto 2003). In the VPC model when the total normalization (intrinsic luminosity) is constant, change of the partial covering fraction causes an **anticorrelation** between the direct (uncovered) spectral component and the absorbed (covered) spectral component below $\sim 10$ keV (figure 4). Thus, flux variations of the direct component and the absorbed component **cancel each other**. The fluxes from these components are the closest to where the absorbing material is the most transparent, just below the iron edge at...
∼7.1 keV. Consequently, the cancellation of the two spectral components works most effectively at around ∼5.5–7 keV, and the fractional variation is reduced (figure 7; see also Inoue et al. 2011; MEI2012). Also, the ∼6.4 keV iron emission line is not expected to vary with the continuum, as it is emitted from outer parts of the accretion disk. These effects work together to reduce the fractional variation at around the iron energy band.

Among the data sets used in this paper, the span of the NGC 5548 observation is the longest: ∼50 days. Its soft X-ray luminosity does vary, by a factor of two over ∼10^6 s, while the covering fraction varies more significantly on much shorter timescales (figure 6). Presumably, the soft X-ray flux variation of Seyfert galaxies has two different origins with different timescales: intrinsic luminosity variation over days and variation of the partial covering fraction on a timescale below a day (see also MES2014).

4.2 Hard X-ray variations

We could fit the variable spectra in 2–10 keV by varying only the partial covering fraction (figures 4 and 5). When the same good time intervals (GTIs) determined based on the XIS counting rates below 10 keV are used for PIN in 10–40 keV, we see some, but not very significant, residuals above ∼10 keV (figure 4): this was also the case for MCG −6−30−15 (MEI2012). Note that in the VPC model, a variation of $\alpha$ hardly affects the spectral variation above ∼10 keV, where the effect of the photoabsorption is at a minimum. Namely, if the hard-tail variations above ∼10 keV were correlated with the intensities
below $\sim 10$ keV, we would have seen much more significant systematic discrepancies above $\sim 10$ keV. Thus, the current results suggest that the hard-tails above $\sim 10$ keV are rather independently variable and averaged when sorted by the intensities below $\sim 10$ keV. In fact, the presence of such independently variable hard components above $\sim 10$ keV is confirmed through a completely different approach for MCG $−6–30–15$ (Noda et al. 2011) and NGC 3516 (Noda et al. 2013). For 1H 0707 $−495$, the VPC model almost perfectly represents the flux variation in 0.5–1 keV on timescales within a day, while less satisfactorily in higher energies (MES2014); this also suggests the commonness of the independently variable hard component in Seyfert galaxies. In summary, we propose that the observed X-ray flux/spectral variation of Seyfert galaxies is explained by a variation of the partial covering fraction on timescales below a day and the intrinsic soft X-ray luminosity variation over $\sim 10^6$ s, both of which are mainly responsible for $\lesssim 10$ keV, and independent hard X-ray variations above $\sim 10$ keV.

4.3 Origin of the optically thick absorbing clouds

From the observed timescales of the X-ray spectral variation and the ionization condition, MEI2012 estimated the sizes and locations of the partial absorbing clouds, and proposed that the partial covering clouds in the VPC model are the broad-line region (BLR) clouds. We revisit this model assuming the BLR parameters estimated from optical observations. We assume the following typical BLR parameters:

- size of BLR, $R \approx 2 \times 10^{16}$ cm;
- BLR cloud size, $l \approx 10^{13}$ cm;
- BLR cloud velocity, $v \approx 5 \times 10^8$ cm s$^{-1}$ (Peterson 2006).

First, the absorbing clouds should be optically thick at the iron K-edge, such that $N_H \approx 2 \times 10^{24}$ cm$^{-2}$, and $\xi \gtrsim 100$ (table 2). The ionization parameter of a BLR cloud may be estimated as follows:

$$\xi = \frac{L}{nR^2} \approx 0.1 \frac{(L/10^{43} \text{ erg s}^{-1})(l/10^{13} \text{ cm})}{(N_H/2 \times 10^{24} \text{ cm}^{-2})(R/2 \times 10^{16} \text{ cm})^2},$$

and thus the assumption of the optical thickness is valid.

Next, we estimate the X-ray emission region size and the variation timescale. We do not see either full covering or no covering, and a typical covering fraction is $\sim 0.5$ (figure 5). Thus, if we take the X-ray emission region size $x$, $(l/x)^2 \approx 0.5$, namely $x \approx 1.4l \approx 1.4 \times 10^{13}$ cm. If normalized by the Schwarzschild radius, $R_S = 1.5 \times 10^{12}(M/5 \times 10^6 M_\odot)\text{ cm}$, $x \approx 10(M_\odot/5 \times 10^6 M_\odot)R_S$. Presumably, this is reasonable as an X-ray emitting corona surrounding the central black hole. Also, the typical flux variation timescale due to passage of a BLR cloud may be estimated at $x/v \approx 3 \times 10^4$ s, which agrees with observations (figure 5).

We notice that, in MCG $−6–30–15$ and the 20 Seyfert galaxies analyzed in this paper, such moderate 6.4 keV emission lines with typical equivalent widths of $\sim 50$ eV are observed, which are consistent with the fluorescence from the distant cold reflectors with $\Omega/2\pi \sim 0.3$ which we assumed. If the central X-ray sources are almost fully surrounded by thick and cold absorbers in these AGNs, much stronger fluorescent lines would have been observed.

---

**Fig. 6.** Top: Variation of the observed XIS counting rates (0.2–12 keV; black, scale at left) and the partial covering fractions (red, scale at right) for NGC 5548. Bottom: Ratio of the total normalizations to the average, indicating the variation of the intrinsic luminosity.
Fig. 7. RMS spectra for the 22 observations. The points are calculated from the data, and the histograms are calculated from the best-fitting spectral models for the time sequence spectra. (Color online)

(e.g., Reynolds et al. 2009). Thus, the weakness of the observed fluorescent emission line suggests that the partial absorbing materials are directional and/or localized, occupying a much smaller solid angle than $4\pi$. It has been pointed out by theoretical simulations that accretion disks in AGNs tend to have disk winds or outflows that imprint a variety of spectroscopic signatures, including absorption lines and edges, in the X-ray/UV spectra (e.g.,
Fig. 7. (Continued) (Color online)

Proga & Kallman 2004; Sim et al. 2010; Nomura et al. 2013). So, the partial covering clouds may be part of such fragmented and directional disk winds or outflows. Furthermore, Doppler motion of the outflowing clouds will smear the narrow emission line features, which would make the fluorescent lines less noticeable.

According to the simulation by Nomura et al. (2013), where the condition of broad absorption line (BAL) quasars is studied, the broad iron K-absorption lines due to the very fast outflow ($\gtrsim 10^4$ km s$^{-1}$) of low-ionized material ($\xi \lesssim 100$) are observed only in a narrow range of the viewing angle between $\theta = 45:6$ and 54:0. When the
viewing angle is larger (closer to edge-on), the BAL will not be produced, as the outflow gas will be too thick \( N_{\text{H}} \gtrsim 10^{24} \text{ cm}^{-2} \) and the velocity will be too low. These conditions are, however, rather suitable for the optically thick partial absorbing clouds required in our VPC model. Thus, the Seyfert galaxies observed through optically thick partial absorbers may be outflowing AGNs seen close to edge-on. In fact, such AGN outflow gas might be the origin of the BLR clouds (Peterson 2006).

### 4.4 Comments on the relativistic disk-line model

Our VPC model explains the observed broad and unvarying iron line features from Seyfert galaxies in terms of fluctuation of the partial absorbers in the line of sight. An alternative model which might explain the broad and unvarying iron line features is the “relativistic disk-line model” (Fabian et al. 2014, and references therein), where the fluorescent iron lines are supposed to be emitted from the innermost region of the illuminated accretion disk, significantly skewed and broadened by strong relativistic effects. In this scenario, suppression of the iron line variability is explained by a relativistic “light-bending effect” (Miniutti & Fabian 2004), where the disk-reflected photons are less variable than the direct photons from the illuminating source, while the height of a point-like illuminating source above the accretion disk varies.

Whereas the light-bending model qualitatively explains the invariability of the broad iron emission line, it does not seem to explain the observed spectral variations quantitatively (see, e.g., Goosmann et al. 2006; Niedźwiecki & Miyakawa 2010; Zycki et al. 2010; Gallo et al. 2015).
The most significant parameter in causing observable spectral changes in the light-bending model is the height of the pointlike source above the accretion disk.

For the light-bending model to remain compelling, it should explain quantitatively the observed spectral variations (figures 4 and 5), as well as the RMS spectra (figure 7) by only changing the source height above the disk.

Presumably, a critical point of the relativistic disk-line model is its extreme concentration of the disk-reflected emission within the innermost region where the relativistic effects are the strongest. For instance, in extreme cases, a prediction was made based on the disk-line model that much of the X-ray emission should originate from within only a few gravitational radii (e.g., Fabian & Vaughan 2003; Fabian et al. 2009). If this is the case, since the AGN is surrounded by many absorbing clouds far outside, when an absorber greater than the X-ray emission region size moves across the line of sight, we shall see an abrupt total eclipse, but never a gradual partial eclipse. However, observational evidence is being accumulated for Seyfert galaxies for which the extended X-ray sources are partially and progressively obscured by intervening absorbers with comparable sizes (e.g., McKernan & Yaqoob 1998; Maiolino et al. 2010; Sanfrutos et al. 2013; Kaasstra et al. 2014; Marinucci et al. 2014; Beuchert et al. 2015). In an occultation event by a BLR cloud far outside identified for MCG − 6–30–15, the partial covering fraction varied gradually by 0.32 within ~ 20 ks (Marinucci et al. 2014). This strongly suggests that the X-ray source is more extended than the absorber, contrary to the assumption of the relativistic disk-line model.

A more unambiguous constraint of the X-ray emission region size may come from X-ray micro-lensing observations. Chartas et al. (2012) observed progressive profile changes of the fluorescent iron emission lines from the gravitationally lensed quasar RX J1131–1231, when the caustic passes over the inner accretion disk. The lines are distorted by general relativistic and Doppler effects, and the line emitting radius is directly measured from these effects as ~ 15 times the gravitational radius. Mosquera et al. (2013) directly measured the X-ray emission region size of Q2237+0305: the half-light radius of the hard X-rays (3.5–21.5 keV) is \( R = 10^{15.5 ± 0.3} \) cm, which is an order of magnitude smaller than that of the optical emission, and marginally smaller than that of the soft X-ray emission (1.1–3.5 keV). It is particularly of interest that the lower limit of the X-ray emission region size is directly constrained. Taking the black hole mass estimates as 0.9 \( \times 10^9 M_\odot \) (Morgan et al. 2010) or 2.4 \( \times 10^9 M_\odot \) (Assef et al. 2011), the hard X-ray emission region sizes (half-light radius) are constrained to 24 ± 3 or 9 ± 2 times the gravitational radius, respectively. These micro-lensing results are consistent with the partial covering scenario where X-ray emission region is extended as much as a few tens of the gravitational radius and comparable in size with the partial absorbing clouds in the line of sight. So that the relativistic reflection scenario works, the innermost disk region has to be sufficiently illuminated, and at least part of the X-ray emitting corona should lie within about 10 gravitational radii (Fabian et al. 2014). Future micro-lensing observations are expected to constrain the lower limit of the X-ray emission region size more tightly, and show whether the relativistic disk-line scenario is truly feasible or not.

5 Conclusions

In this paper, we have studied the origin of the soft X-ray spectral variation and broad iron line feature commonly observed in Seyfert galaxies. We have applied the variable partial covering model, which has been successful for MCG − 6–30–15 (Miyakawa et al. 2012) and 1H 0707−495 (Mizumoto et al. 2014), to 20 other Seyfert galaxies observed with Suzaku. In the VPC model, most spectral variations below ~ 10 keV in a timescale within ~ 1 day are explained by the variation of the partial covering fraction of the extended X-ray source due to fluctuations of the optically thick absorbing clouds in the line of sight. Not only the broad iron line features, but also the 2–10 keV spectral variations are successfully explained by the VPC model. We conclude that the observed X-ray flux/spectral variation of Seyfert galaxies is explained by the variation of the partial covering fraction in timescales below a day, and the intrinsic soft X-ray luminosity variation over ~ 10^6 s, both of which are mainly responsible for \( \lesssim 10^5 \) keV, and independent hard X-ray variations above ~ 10 keV.

Acknowledgement

This research has made use of public Suzaku data obtained through the Data ARchives and Transmission System (DARTS) provided by the Institute of Space and Astronautical Science (ISAS) at the Japan Aerospace Exploration Agency (JAXA). For data reduction, we used software provided by the High Energy Astrophysics Science Archive Research Center (HEASARC) at NASA/Goddard Space Flight Center. HS is financially supported by JSPS Grant-in-Aid for JSPS Fellows Grant Number 12J0755, and MM is supported by JSPS KAKENHI Grant Number 15J07567.

References

Assef, R. J., et al. 2011, ApJ, 742, 93
Beuchert, T., et al. 2015, A&A, 584, A82
Boldt, E. 1987, Phys. Rep., 146, 215
Chartas, G., Kochanek, C. S., Dai, X., Moore, D., Mosquera, A. M., & Blackburne, J. A. 2012, ApJ, 757, 137
Edelson, R., Turner, T. J., Pounds, K., Vaughan, S., Markowitz, A., Marshall, H., Dobbie, P., & Warwick, R. 2002, ApJ, 568, 610
Fabian, A. C., et al. 2002, MNRAS, 335, L1
Fabian, A. C., et al. 2009, Nature, 459, 540
Fabian, A. C., Parker, M. L., Wilkins, D. R., Miller, J. M., Kara, E., Reynolds, C. S., & and Dauser, T. 2014, MNRAS, 439, 2307
Fabian, A. C., & Vaughan, S. 2003, MNRAS, 340, L28
Fukazawa, Y., et al. 2009, PASJ, 61, S17
Gallo, L., et al. 2015, MNRAS, 446, 633
Goosmann, R. W., Czerny, B., Mouchet, M., Ponti, G., Dovčiak, M., Karas, V., Róžańska, A., & Dumont, A.-M. 2006, A&A, 454, 741
Inoue, H., & Matsumoto, C. 2003, PASJ, 55, 625
Inoue, H., Miyakawa, T., & Ebisawa, K. 2011, PASJ, 63, S669
Ishisaki, Y., et al. 2014, Science, 345, 64
Kokubun, M., et al. 2007, PASJ, 59, S53
Koyama, K., et al. 2007, PASJ, 59, S23
Magdziarz, P., & Żdziarski, A. A. 1995, MNRAS, 273, 837
Maiolino, R., et al. 2010, A&A, 517, A47
Marinucci, A., et al. 2014, ApJ, 787, 83
Matsumoto, C., Inoue, H., Fabian, A. C., & Iwasawa, K. 2003, PASJ, 55, 615
Matsuoka, M., Piro, L., Yamauchi, M., & Murakami, T. 1990, ApJ, 361, 440
McKernan, B., & Yaqoob, T. 1998, ApJ, 501, L29
Miller, L., Turner, L. J., & Reeves, J. N. 2008, A&A, 483, 437
Miniutti, G., & Fabian, A. C. 2004, MNRAS, 349, 1435
Mitsuda, K., et al. 2007, PASJ, 59, S1
Miyakawa, T., Ebisawa, K., & Inoue, H. 2012, PASJ, 64, 140 (MEI2012)
Mizumoto, M., Ebisawa, K., & Sameshima, H. 2014, PASJ, 66, 122 (MES2014)
Morgan, C. W., Kochane, C. S., Morgan, N. D., & Falco, E. E. 2010, ApJ, 712, 1129
Mosqueria, A. M., Kochaneck, C. S., Chen, B., Dai, X., Blackburne, J. A., & Chartas, G. 2013, ApJ, 769, S3
Mushotzky, R. F., Done, C., & Pounds, K. A. 1993, ARA&A, 31, 717
Niedźwiecki, A., & Miyakawa, T. 2010, A&A, 509, 22
Noda, H., Makishima, K., Nakazawa, K., & Yamada, S. 2013, ApJ, 771, 100
Noda, H., Makishima, K., Uehara, Y., Yamada, S., & Nakazawa, K. 2011, PASJ, 63, 449
Nomura, M., Ohshima, K., Wada, K., Susa, H., & Misawa, T., 2013, PASJ, 65, 40
Peterson, B. M. 2006, in The Broad-Line Region in Active Galactic Nuclei, ed. D. Alloin et al. (Berlin: Springer-Verlag), 77
Proga, D., & Kallman, T. R. 2004, ApJ, 616, 688
Reynolds, C. S., Fabian, A. C., Brenneman, L. W., Miniutti, G., Uttley, P., & Gallo, L. C. 2009, MNRAS, 397, L21
Sanfrutos, M., Miniutti, G., Agis-González, B., Fabian, A. C., Miller, J. M., Panessa, F., & and Zoghbi, A. 2013, MNRAS, 436, 1588
Serlemitsos, P. J., et al. 2007, PASJ, 59, S9
Sim, S. A., Proga, D., Miller, L., Long, K. S., & Turner, T. J. 2010, MNRAS, 408, 1396
Takahashi, T., et al. 2007, PASJ, 59, S33
Tanaka, Y., et al. 1995, Nature, 375, 659
Urry, M.-H., Maraschi, L., & Urry, C. M. 1997, ARA&A, 35, 445
Zycki, P. T., Ebisawa, K., Niedźwiecki, A., & Miyakawa, T. 2010, PASJ, 62, 1185