Fe–K LINE TIME VARIABILITY AND Ni ABUNDANCE OF DISTANT REFLECTORS IN SEYFERT GALAXIES

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ABSTRACT

We have performed systematic studies of narrow Fe–K line (6.4 keV) flux variability and Ni–K line intensity for Seyfert galaxies, using Suzaku and XMM-Newton archival data. Significant Fe–K line variability of several tens of percent was detected for a pair of observations separated by 1000–2000 days (Cen A, IC 4329 A, NGC 3516, and NGC 4151) and 158 days (NGC 3516). These timescales are larger by a factor of 10–100 than the inner radius of the torus, consistent with the view that X-ray reflection by a torus is a main origin for a narrow Fe–K line. The Ni–K line was detected with a >2σ level for the Circinus galaxy, Cen A, MRK 3, NGC 4388, and NGC 4151. A mean and variance of the Ni–Kα to Fe–Kα line intensity ratios are 0.066 and 0.026, respectively. Comparing this with the Monte-Carlo simulation of reflection, the Ni to Fe abundance ratio is 1.9 ± 0.8 solar. We discuss the results and the possibility of Ni abundance enhancement.

Key words: galaxies: active – X-rays: galaxies

1. INTRODUCTION

The X-ray spectra of active galactic nuclei (AGNs) exhibit various reprocessed features such as continuous absorption, fluorescence lines, reflection humps, absorption lines, and so on. Among them, fluorescence lines and reflection humps are prominent in the hard X-ray band. Reflection is believed to be mainly attributed to an accretion disk or a distant torus (Pounds et al. 1990; Awaki et al. 1991), but a broad line region (BLR) is also suggested to be an origin (Yaqoob & Padmanabhan 2004; Nandra 2006). Here we do not deal with a relativistic reflection from the inner accretion disk. The origin of the torus and the connection to the BLR and accretion disk are important topics to understand the formation of the accretion disk and the evolution of central massive black holes.

The structure of the torus is not yet completely established. Optical polarization and far-infrared (FIR) observations indicate that a torus exists with a size of ∼100 pc (Antonucci 1993; Pier & Krolik 1993). Recent near-infrared (NIR) observations measured an inner torus radius as 0.03L1/5 15 pc (Suganuma et al. 2006), where L1 is a luminosity of the central engine in units of 1043 erg s–1. A clumpy torus is suggested to understand a large geometrical thickness (Wilson & Tsvelanov 1994), FIR spectral features (Nenkova et al. 2002), variable X-ray absorption (Risaliti et al. 2002), and so on.

The origin of narrow Fe–K lines in the AGN spectra is considered to be the torus (Awaki et al. 1991), and a line center energy supports this view (Yaqoob & Padmanabhan 2004; Fukazawa et al. 2011a). On the other hand, it is suggested that there is a contribution of the inner region to the narrow Fe–K lines, such as the BLR or the outer accretion disk, based on a wide range of narrow Fe–K line widths (Nandra 2006; Bianchi et al. 2008) or a lack of Compton-thick reflection hump (Ursini et al. 2015).

The variability of Fe–K line flux is also a good probe to constrain the emission region. Searching for Fe–K line flux variability has been attempted, but little evidence has been reported. This is because a signal-to-noise ratio of Fe–K lines is not sufficient for the past observations, and Suzaku or XMM-Newton observations are needed. There are several reports about the flux variability of the Fe–K line. A short variability timescale of a sub-day was reported for MRK 841 (Petrucci et al. 2002; Longinotti et al. 2004). On the other hand, a year-long timescale variability was reported for Cen A (Fukazawa et al. 2011b), NGC 7213 (Ursini et al. 2015), and NGC 2110 (Marinucci et al. 2015). Shu et al. (2012) systematically studied the Chandra/HETG data of 32 AGNs and concluded that the Fe–Kα line flux lacks a corresponding response to the continuum variation, but the photon statistics are limited and a timescale on the study is typically much shorter than one year. Therefore, systematic studies of Fe–K line variability with good photon statistics and various timescales are needed.

Metal abundance of reflectors can be measured from the fluorescence lines of several elements. High-quality XMM-Newton data for the first time resolve the Ni–K line for a few AGNs. The Ni to Fe Kα line ratio was reported to be 0.070 ± 0.010 for the Circinus galaxy, 0.13 ± 0.03 for NGC 1068 (Matt et al. 2004), and 0.067 ± 0.034 for MRK 3 (Pounds & Vaughan 2006). Suzaku also detected fluorescence lines other than Fe–K from bright AGNs, such as Cen A (Markowitz et al. 2007), MRK 3 (Awaki et al. 2008), and the Circinus galaxy (Yang et al. 2009). However, systematic measurements of fluorescence lines other than Fe–K have not yet been performed. The metal abundance of a torus is interesting in terms of its connection with the BLR and accretion disk. The metal abundance of BLR is reported to be supersolar by optical/UV observations (Warner et al. 2004). On the other hand, it is suggested that there is a contribution of the inner region to the narrow Fe–K lines, such as the BLR or the outer accretion disk, based on a wide range of narrow Fe–K line widths (Nandra 2006; Bianchi et al. 2008) or a lack of Compton-thick reflection hump (Ursini et al. 2015).

In this paper, we report systematic studies of Fe–K line flux variability and Ni abundances, based on archival Suzaku
(Mitsuda et al. 2007) data on Seyfert galaxies with good photon statistics, due to its large effective area and repeated observations. In addition, we utilized some archival *XMM-Newton* data in order to compensate the variability timescale of 0.5–1 year. Throughout this paper, the errors are shown as a 90% confidence level. The solar abundance ratio is referred to the solar photospheric values of Anders & Grevesse (1989) for photoelectric absorption, reflection, and plasma model, and the cross-section for absorption model is set to that of Balucinska-Church & McCammon (1992).

2. OBSERVATIONS AND DATA REDUCTION

We analyzed the archival *Suzaku* data of X-ray-bright AGNs. The selection of sample AGNs is the same as Fukazawa et al. (2011a); they are detected by HXD-PIN (Kokubun et al. 2007; Takahashi et al. 2007) above 15 keV. This ensures a high signal-to-noise ratio around the Fe–K lines. Also, the time variability of the central engine can be traced above 10 keV freely from absorption. In addition, X-rays above 7 keV are important to produce Fe–K line photons. As a result, we looked at 261 observational data of 173 objects. All the data were obtained with the standard mode of XIS (5 × 5 or 3 × 3) and HXD. Data reduction of XIS (Koyama et al. 2007) and HXD-PIN is also the same as Fukazawa et al. (2011a), following the *Suzaku* data reduction. We then extracted the spectra of each XIS-FI (0, 2, 3) and XIS-BI (1) within 4 arcmin of the object, and the XIS-FI spectra were coadded; after 2006 November, XIS-2 data were not available, and thus we analyzed only XIS-0 and XIS-3 for the XIS-FI data. In the line studies, we fitted XIS-FI and XIS-BI spectra simultaneously with the cross normalization set to be free.

For the analysis of Fe–K line variability, we selected AGNs that have been observed multiply with *Suzaku*. Furthermore, we gave criteria that a photon count after background subtraction is more than 2500 in 5–9 keV. In addition, we do not include objects with strong Fe–K absorption lines: NGC 1365, MRK 766, MRK 335, PDS 456, and Fairall 51. H1821+643 is excluded since the Fe–Kα line is not detected for all observations in the following analysis. As a result, 88 observational data of 25 objects are analyzed for the study of Fe–K flux variability. Table 1 summarizes the data we analyzed for Fe–K line variability.

For the analysis of the Ni–K line, we analyzed data whose observed photon count of XIS-FI after background subtraction is more than 5000 in 5–9 keV. Furthermore, we set a criteria for target selection that the degree of freedom in the fitting of the 7.1–8.0 keV band is more than 3 (for details, see Section 3.2). As a result, 143 out of 261 observations remain for studies of the Ni–K line.

Since there are only a few pairs of *Suzaku* observations with a separation of 0.5–1 year, we analyzed archival *XMM-Newton* data of objects which has been observed by *Suzaku* repeatedly in order to study the Fe–K line variability with a timescale of 0.5–1 year. For such objects, we searched for pairs of observations with a separation around 0.5–1 year, and found that nine objects have such a pair of observations. Table 2 summarizes the *XMM-Newton* data we analyzed for Fe–K line variability. We performed the standard data reduction with *SAS* 14.0.0. We extracted the source and background spectra and generated the response functions with *xmmextractor*. We fitted MOS-1, MOS-2, and PN spectra simultaneously with the cross normalizations set to be free.

3. RESULTS

3.1. Fe–K Line Variability

In order to derive the Fe–K line flux, we fitted the XIS spectra in 5–9 keV. In addition, we ignored the energy band of XIS-1 where the flux is less than 0.02 count s$^{-1}$ keV$^{-1}$, to avoid the background uncertainty. The continuum shape is determined by fitting the 2–10 keV XIS and 15–50 keV PIN spectra by the model including an partially absorbed power law and a reflection component. The reflection component is modeled by *pexmon* (Nandra 2006) with the inclination and high-energy cutoff fixed to 60° and 1000 keV, respectively. Partial absorption is modeled by *zphabs* and *pcfabs*. We determined the continuum parameters, and used them in the fitting of the Fe–K line region (5–9 keV) by fixing the parameters of the absorption model of *zphabs* and *pcfabs*, and reflection fraction. Then, we replaced the model *pexmon* by the model *pexrav* (Magdziarz & Zdziarski 1995), where only the reflection continuum is considered. As a result, free parameters of the continuum model are a photon index and a normalization of the power law. In addition, we included five gaussians which represent three fluorescence lines of Fe–Kα (6.394 keV), Fe–Kβ (7.08 keV), and Ni–Kα (7.47 keV), and two ionized Fe–Kα lines of He-like (6.7 keV) and H-like (7.0 keV), by the model *zgaussian*. The ionized Fe–Kα lines represent ionized emission or absorption lines observed in many AGNs (Fukazawa et al. 2011a), and we represent them by a positive or negative normalization of *zgaussian* model. Note that consideration of these two lines in the fitting introduces some additional errors to the fluorescence Fe–Kα line intensity. The energies of lines other than the 6.4 keV line are fixed to the rest-frame energy and shifted by redshift, and the widths of these lines are fixed to 0. The normalization ratio of the fluorescence Fe–Kβ to the Kα line is fixed to 0.125 (Palmeri et al. 2003). The above modeling is the same as done in Fukazawa et al. (2011a). As a result, the fits are almost successful with a reduced $\chi^2$ of $<1.5$. Two exceptions are NGC 4151 (2012) and NGC 3783 (2009), where a low-energy tail structure at the left side of the Fe–Kα line exists and thus their reduced $\chi^2$ is $>2$. This structure could be reproduced by the relativistic reflection model (Reynolds et al. 2012; Keck et al. 2015). Here, we added the broad Gaussian but the narrow Fe–Kα line flux does not change beyond statistical errors; we treat only the narrow line for the Fe–K line variability study. Two observations of NGC 4945 (2010 July 9) and MRK 841 (2007 July) give a somewhat worse fit with a reduced $\chi^2$ of $\sim2$, and thus we do not treat these data. We took an average of the line flux of XIS-FI and XIS-BI, weighting them at 3:1, considering the observed number of photons. The difference between the XIS-FI line flux and the average one is added to the statistical error as a systematic error. In most cases, the difference is at most 2%, but it is sometimes up to 5%. As a result, the obtained Fe–Kα line flux of 88 observations (25 objects) is summarized in Table 1. When we changed the fitting energy range to 6.0–8.0 keV, we obtained consistent Fe–Kα line flux within errors. In order to quantify the flux variability of the central engine, we fitted the PIN spectra in 15–70 keV by power law and derived the flux in 20–30 keV.

For *XMM-Newton* data, we analyzed the spectra in 5–8 keV by modeling the absorbed power law plus 5 gaussians const*(phabs*powerlaw+5*zgaussian) since the reflection continuum cannot be constrained by only *XMM-Newton* and is
not significantly contributed to the Fe−K band for analyzed data, according to the *Suzaku* data. Five *gauasian* models were treated in the same way as the *Suzaku* data analysis. All the spectra were well fitted by this modeling with the reduced χ² < 1.1. We also checked the pile up by looking at the plots created with the tool *evalplot* and comparing the constant factors of each instrumental spectra. Then, the data of the brightest object Cen A suffered significantly from the pile up, and other objects often have a scatter of constant factors with ~10% difference between MOS-1 and MOS-2, and often with a larger difference between MOS and PN. Therefore, we did not treat Cen A data here. For other objects, we took an average of the line flux of MOS-1 and MOS-2, and the difference between MOS-1 line flux and the average one is added to the statistical error as a systematic error. The results are summarized in Table 2.

Figure 1 shows the variability fraction of the Fe−K line flux against the separation time Δt for a pair of two sequence observations. The error bars represent the 1σ level, and the stars and crosses represent the upper limits. AGNs with significant variability of the Fe−K line flux are indicated in Table 1. Since the objects have been observed as do not know, we do not show the complete history of the flux variability of the central engine, and thus we cannot consider whether or not the objects are
expected to show a variability of Fe–K line flux. *Suzaku* measured the direct emission flux almost free from the absorption with PIN, and thus the PIN flux can be used as an indicator of variability of the central engine. Therefore, we plot the data with different symbols whether the PIN flux variance among all observations is $>30\%$ (square, star) or not (triangle, cross), and whether the PIN flux variability between a pair of observations is $>30\%$ (filled) or not (open). The latter is a direct evidence of flux variability. The former ensure that the objects varies significantly even if the flux does not vary between a corresponding pair of observations. If the flux variability is not significant, we give an upper limit. $\Delta t$ is concentrated on $<50$ days and $>1000$ days. The data with $\Delta t < 50$ days are monitoring observations within one observable window (several months), while those of $\Delta t > 1000$ days are reobservations after several years from the past observations. Several pairs of observations show a significant Fe–K line variability of several percent with $>2\sigma$ level for $\Delta t > 1000$ days; Cen A, IC 4329A, NGC 3516 (2 pairs), and NGC 4151. On the other hand, some objects show a possible variability with $(1-2)\sigma$ level Cen A, NGC 3227, NGC 5548 in $\Delta t < 20$ days, NGC 3516, NGC 3783, NGC 4151 in $\Delta t = 200-350$ days, and 3C 120, 3C 390.3, MCG-5-23-16, NGC 2110 in $\Delta t > 2000$ days. The Fe–K line intensity is high, but the equivalent width is not so large and the exposure time is not so long, and thus the signal-to-noise ratio is low. One object, NGC 3516, with a separation of 158 days shows a significant Fe–K variability of $\sim 50\%$. This timescale is much shorter than those of significant variability at $\Delta t > 1000$ days. We return to this issue in the discussion.

### 3.2. Ni–Kα Line Intensity

By using the same model as used in the Fe–K line analysis, we obtained the Ni–Kα line flux. Figure 2 shows an example of the observed Ni–Kα line. The Circinus galaxy, which has the highest Fe–K line flux (Fukazawa et al. 2011b), shows a clear Ni–K line, while some other AGNs show a marginal Ni–K line as NGC 4388. Since a Ni–Kα line is very weak ($1/20 \sim 1/30$ times as intense as the Fe–K line), we limited the energy band to 7.1–8.0 keV to avoid a situation in which the continuum level mismatch causes an incorrect Ni–Kα line flux. The line parameters other than the Ni–Kα line are fixed to those of Fe–K line analysis. The spectra are well fitted with a reduced $\chi^2$ of $<2$ in all observations. Although the Ni–Kα line was not significantly detected for most observations due to a weakness of the Ni–K line, 16 observational data (9 objects) show a significance of $>1\sigma$ for Ni–Kα line detection. Figure 3 plots a line flux ratio of Ni–Kα to the Fe–K line $I_{\text{Ni}/I_{\text{Fe}}}$ for these 16 observations, and Table 3 summarizes the results. The Ni–Kα line fluxes of Cen A (2005), MRK 3, and the Circinus galaxy are consistent with those in the past results of *Suzaku* observations (Markowitz et al. 2007; Awaki et al. 2008; Yang et al. 2009). The average of $I_{\text{Ni}/I_{\text{Fe}}}$ is 0.066 with a variance of 0.026 for measurements of single observation. The most accurate measurement was obtained to be $I_{\text{Ni}/I_{\text{Fe}}} = 0.0486 \pm 0.0066$ for the Circinus galaxy, whose equivalent width of the Ni–Kα line is the largest. Several other AGNs also provide a mild measurement for Cen A, MRK 3, NGC 4388, and NGC 4151, but the Ni–K line significance is not so high.

When we changed the fitting energy range to 7.1–7.8 keV, we obtained consistent Ni–Kα flux within errors. We then modeled the continuum by only the absorbed power law (phabs+powerlaw in XSPEC) instead of the above model (which contains partial covering absorption and reflection), Ni–Kα flux does not change within errors. Exceptional cases are the results of the Circinus galaxy and NGC 4151, whose spectra around the Fe–K edge cannot be well represented by the simple absorbed power-law model, and thus their Ni–Kα flux changes due to the incompleteness of continuum modeling.

In addition to data analysis of single pointing observations, we summed the spectra of multiple observations for objects which were repeatedly observed, and analyzed them in the same way as data of a single observation. We also plot the results in Figure 3 (black circle). The Ni–K line intensity ratio of multiple observations is systematically larger than that of a single observation. For Cen A and NGC 4151, they were observed during the bright state several times and the Ni–K line equivalent width became small. Therefore, the summation of multiple observations does not necessarily increase the signal-to-noise ratio and thus does not give a confident result. Therefore, we do not refer to results of multiple observations.
Fractional Fe–K variability against the separation time with the previous observation. Error bars represent 1σ. Red and green data have a significance of variability with $>2\sigma$ and $(1-2)\sigma$, respectively. Squares with solid error bars and stars represent objects whose PIN flux variance among all observations is $>30\%$, while triangles with dashed error bars and crosses represent objects which do not. Stars and crosses are upper limits for objects with no significant Fe–K line variability for PIN flux variance with $>30\%$ and $\leq 30\%$, respectively. Filled and open data correspond to objects whose PIN flux variabilities between a pair of observations are $>30\%$ or $\leq 30\%$, respectively. The right panel is an enlargement for $\Delta t > 1000$ days. “XMM” indicates the result derived with the XMM-Newton data.

4. DISCUSSION

The Fe–K line flux of bright AGNs is typically around $10^{-5}$ photons s$^{-1}$ cm$^{-2}$ and thus an effective area of $>100$ cm$^2$ around 6 keV is needed to obtain a 10% accuracy with 100 ks observation. Actually, a more effective area is needed to reduce a Poisson noise of continuum. Therefore, Suzaku XIS and XMM-Newton provide opportunities of Fe–K variability study. As a result, we obtained the results that some objects show a significant Fe–K variability of several tens of percent with $\Delta t > 1000$ days. This is an extensive result of the past reports (Fukazawa et al. 2011b; Marinucci et al. 2015; Ursini et al. 2015). On the other hand, clear evidence of Fe–K variability with $\Delta t < 50$ days is not found. These facts are consistent with the view that a fluorescence narrow Fe–K line originates at the distant torus.

Figure 4 plots the separation timescale between a pair of observations against the X-ray luminosity in 20–30 keV. For the XMM-Newton results, we converted the absorption-corrected 2–10 keV flux to the 20–30 keV luminosity by using the power law with a photon index of 1.7. We also plot the inner radius of the torus measured by dust echo (Suganuma et al. 2006); we adjust the scale by NGC 5548 with the V magnitude of $-19.12$ (Suganuma et al. 2006) and X-ray luminosity (20–30 keV) of $6.64 \times 10^{42}$ erg s$^{-1}$. The observed timescale of the Fe–K line variability is 10–100 times as large as the inner radius of the torus. The Fe–K line variability can appear if the central emission varies with a large amplitude of $>50\%$, and timescale of such a large variability is typically around several months. On the other hand, Fe–K line variability will not be observed when the separation timescale between a pair of observations is shorter than the variability timescale of the central emission. Considering these effects, the separation timescale between a pair of observations where Fe–K variability is observed is biased to a longer timescale than a true light crossing time of the Fe–K emitting region. Therefore, the observed timescale of the Fe–K line variability is larger than the inner radius of torus. On the other hand, the Fe–K line variability will be smeared when the central emission varies with a shorter timescale than the light crossing time of the Fe–K emitting region. The fact that the Fe–K line varies with a separation timescale of 1000–2000 days between a pair of observations indicates that the Fe–K emitting region extends to $\sim 1$ pc. Therefore, our results suggest that the Fe–K line emitting region in some AGNs is mainly the dust torus within 1 pc of the center, but does not conflict with some contribution of the BLR to the Fe–K line, as suggested by Minezaki & Matsushita (2015) or Gandhi et al. (2015).

One special example of significant Fe–K variability is NGC 3516, whose Fe–K line intensity varied by $\approx 50\%$ with $\Delta t = 180$ days. This variability was observed between 2013 May and November, when the flux of NGC 3516 was historically low in November. It is suggested that the inner radius of torus becomes smaller due to the low X-ray luminosity of $(0.5-2.5) \times 10^{42}$ erg s$^{-1}$ (15–50 keV) in 2013–2014. A detailed analysis of NGC 3516 will be presented in a forthcoming paper.

CCD energy resolution is around 120 eV at the Fe–K line and typical equivalent widths of the Fe–K line for non-Compton-thick Seyfert galaxies are 50–200 eV (Fukazawa et al. 2011a). Therefore, in most cases, the Poisson noise of the continuum significantly contributes to the line flux accuracy. ASTRO-H SXS has an unprecedentedly good energy resolution of 4–6 eV (Takahashi et al. 2014), enabling us to measure the Fe–K line flux more accurately without contribution of continuum. Also, ASTRO-H SXS could measure the Fe–K line width with good accuracy, and time variability study could track the width variation and thus the change of inner torus radii.

Suzaku XIS observations also enabled us to measure the Ni–Kα line flux of AGNs systematically for the first time, due to its stable and low background. $I_{\text{Ni}/I_{\text{Fe}}}$ is 0.03–0.07 for objects with Ni line detection. These are almost consistent with the past observations of XMM-Newton and Suzaku, but smaller than $0.13 \pm 0.03$ of XMM-Newton measurements for NGC 1068 (Matt et al. 2004). Since Ni–K line is very weak, it could be affected by background subtraction or complex absorption features by highly ionized material. The former case would not be worried about in our results, since most objects with Ni–K line detection are apparently bright. Here, we discuss the Ni–Kα intensity ratio to the Fe–Kα, by considering the latter case.

The predicted Ni–K line intensity in the reflection spectrum of AGNs has been reported by Yaqoob & Murphy (2011) in detail based on their MYTorus model. They assumed that the Ni to Fe abundance ratio is the same as that of Anders &
red data represent objects with the Fe abundance ratio was reported to be larger by a factor of 1.5–2.0 solar, the Fe–Kα to Ni–Kα line intensity ratio varies almost proportionally to the assumed Ni abundance. Since the assumed abundance and fluorescence yield of Ni in our paper and Yaqoob & Murphy (2011) is explicitly shown and typically used, we take the Ni to Fe Kα line ratio of 0.035 ± 0.003 for the solar abundance. In this case, the average of the observed Ni to Fe Kα line flux ratios of 0.062 ± 0.026 indicates that the Ni to Fe abundance ratio is 1.9 ± 0.8 solar, and it is marginally consistent with but somewhat higher than the solar abundance ratio. The Ni to Fe abundance ratio was reported to be larger by a factor of 1.5–2.0 than that of Anders & Grevesse (1989) for the Circinus galaxy (Molendi et al. 2003), and thus consistent with ours. This suggests possible evidence of enhanced Ni to Fe abundance ratio for the torus material of AGNs. Note that the XMM-Newton results of NGC 1068 (Molendi et al. 2003) lead to the extremely large Ni to Fe abundance ratio of 3.7 ± 0.9 solar.

However, as described in Section 3.2, we must pay attention to the continuum modeling in measurements of a weak Ni–Kα fluorescence yield for the database used in pexmon.

As an independent check, we performed the Monte-Carlo simulation of X-ray reflection by torus using the Geant 4 package, as performed by Odaka et al. (2011) or Liu & Li (2014), using the framework MONACO (Odaka et al. 2011). A detailed description on this Monte-Carlo simulation will be presented in Furui et al. (2016). The geometry is almost the same as that of Murphy & Yaqoob (2009). We assume Fe and Ni abundances, according to Anders & Grevesse (1989). The fluorescence yield (Kα branching fraction) of the K lines is 0.3401 (0.8830) and 0.4060 (0.8825) for Fe and Ni, respectively (Furui et al. 2016). The absorption column density of the torus is assumed to be 10^{24.5} cm^{-2} toward the equatorial direction. The incident X-rays follow a power-law shape with a photon index of 2 in the range of 2–300 keV. The reflection spectrum is accumulated with a viewing angle of θ as 0.1 < cos θ < 0.2, convolved with the XIS response function, and fitted in the same way as observed data. As a result, a Fe–Kα (6.4 keV) to Ni–Kα line intensity ratio becomes 0.035, almost consistent with that based on Yaqoob & Murphy (2011). When we change the assumed Ni abundance to 0.5 solar or 2.0 solar, the Fe–Kα to Ni–Kα line intensity ratio varies almost proportionally to the assumed Ni abundance. Since the assumed abundance and fluorescence yield of Ni in our paper and Yaqoob & Murphy (2011) is explicitly shown and typically used, we take the Ni to Fe Kα line ratio of 0.035 ± 0.003 for the solar abundance. In this case, the average of the observed Ni to Fe Kα line flux ratios of 0.062 ± 0.026 indicates that the Ni to Fe abundance ratio is 1.9 ± 0.8 solar, and it is marginally consistent with but somewhat higher than the solar abundance ratio. The Ni to Fe abundance ratio was reported to be larger by a factor of 1.5–2.0 than that of Anders & Grevesse (1989) for the Circinus galaxy (Molendi et al. 2003), and thus consistent with ours. This suggests possible evidence of enhanced Ni to Fe abundance ratio for the torus material of AGNs. Note that the XMM-Newton results of NGC 1068 (Molendi et al. 2003) lead to the extremely large Ni to Fe abundance ratio of 3.7 ± 0.9 solar.

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line. Possible systematics are caused by blueshifted Fe–K absorption lines. Typical weak blueshifted Fe–K absorption lines have an equivalent width of 10–30 eV (Tombesi et al. 2010). If such absorption lines exist in the CCD spectra but are not modeled in the narrowband spectral fitting around the Ni–K line, the continuum would be underestimated and thus the Ni–K line equivalent width would be affected by ~10 eV. Equivalent widths of observed Ni–Kα lines are typically 5–20 eV, and thus could be overestimated by several percent. This indicates that the measurement with higher spectral resolution is important to determine a Ni–K line flux unambiguously. Therefore, ASTRO-H SXS (Takahashi et al. 2014) observations of AGNs are promising for Ni–K line probing.

The enhanced abundance of Ni has recently been reported for a supernova remnant 3C 397 whose progenitor is considered to be a SN Ia (Yamaguchi et al. 2015), who suggested a production of $^{58}\text{Ni}$ in the single-degenerated binary. The enhanced Ni to Fe ratio has also been reported for other galaxies and AGNs is important to understand star formation phenomena, which are often associated with AGN–hosting galaxies. These issues are related with star formation phenomena, which are often associated with AGN activity. Therefore, information of Ni to Fe abundance ratio in other galaxies and AGNs is important to understand star formation history of galaxies and AGNs.

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Figure 4. Observation separation time of a pair of observations against X-ray luminosity in 20–30 keV. Red squares, black squares, and green circles are observations with the Fe–K variability of >2σ, (1–2)σ, <1σ level, respectively. A solid line represents an inner radius of torus measured by dust echo (Suganuma et al. 2006).

Table 3
Summary of Observed Fe–Kα and Ni–Kα Line Flux

| Object       | Obs | Fe–Kα | Fe–EW | Ni–Kα | Ni–EW | Reduced χ² (dof) |
|--------------|-----|-------|-------|-------|-------|-----------------|
| CIRClNUS     | 060721 | 337 ± 4.9 | 1435 ± 21 | 17.1 ± 2.5 | 142.4 ± 10.5 | 1.52 (23) |
| Cen_A        | 050819 | 228.5 ± 10.7 | 69 ± 3 | 16.8 ± 2.9 | 7.4 ± 1.3 | 1.16 (112)  |
| Cen_A        | 090720 | 327.1 ± 17.0 | 63 ± 3 | 45.5 ± 13.8 | 12.9 ± 4.1 | 1.08 (120)  |
| Cen_A        | 090805 | 361.5 ± 18.4 | 75 ± 4 | 20.0 ± 3.5 | 5.9 ± 0.5 | 1.05 (116)  |
| Cen_A        | 090814 | 341.9 ± 18.4 | 63 ± 3 | 20.2 ± 3.5 | 5.3 ± 0.4 | 1.04 (120)  |
| Cen_A        | 140106 | 317.8 ± 41.2 | 103 ± 13 | 48.0 ± 36.2 | 22.2 ± 16.7 | 1.41 (24)  |
| IC 4329A     | 070816 | 67.2 ± 13.1 | 59 ± 11 | 15.4 ± 10.9 | 19.5 ± 13.9 | 1.10 (22)  |
| MCG+8-11-11  | 070917 | 50 ± 4.9 | 68 ± 7 | 4.1 ± 0.4 | 7.7 ± 0.2 | 0.85 (63)  |
| MCG-5-23-16  | 051207 | 79.4 ± 6.1 | 73 ± 6 | 7.8 ± 4.2 | 10.2 ± 4.4 | 1.27 (77)  |
| MRK 3        | 051022 | 50.2 ± 2.6 | 427 ± 22 | 3.5 ± 1.7 | 60.2 ± 29.0 | 0.71 (9)    |
| NGC 2110     | 150320 | 88.5 ± 8.8 | 94 ± 9 | 12.0 ± 7.4 | 18.1 ± 11.2 | 1.32 (43)  |
| NGC 4151     | 061218 | 168.1 ± 5.3 | 266 ± 8 | 9.4 ± 3.4 | 22.1 ± 7.7 | 0.96 (66)  |
| NGC 4151     | 111117 | 275.3 ± 12.7 | 92 ± 4 | 11.1 ± 9.0 | 5.4 ± 3.0 | 1.10 (106) |
| NGC 4151     | 111218 | 275.6 ± 13.0 | 87 ± 4 | 15.0 ± 10.4 | 6.9 ± 2.0 | 1.31 (107) |
| NGC 4388     | 121111 | 256.9 ± 7.5 | 102 ± 3 | 13.5 ± 6.6 | 8.2 ± 1.4 | 1.50 (120) |
| NGC 4388     | 051224 | 77.5 ± 3.3 | 207 ± 9 | 5.4 ± 2.1 | 23.8 ± 10.2 | 0.90 (39)  |

Notes.

a Observation date with YYMMDD.
b Line flux in units of $10^{-6}$ photons s$^{-1}$ cm$^{-2}$.
c Reduced χ² (dof).
