SUZAKU MONITORING OF THE IRON K EMISSION LINE IN THE TYPE 1 ACTIVE GALACTIC NUCLEUS NGC 5548

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ABSTRACT

We present seven sequential weekly observations of NGC 5548 conducted in 2007 with the Suzaku X-ray Imaging Spectrometer (XIS) in the 0.2–12 keV band and Hard X-ray Detector (HXD) in the 10–600 keV band. The iron Kα line is well detected in all seven observations and Kβ line is also detected in four observations. In this paper, we investigate the origin of the Fe K lines using both the width of the line and the reverberation mapping method. With the co-added XIS and HXD spectra, we identify Fe Kα and Kβ line at 6.396±0.007 keV and 7.08±0.05 keV, respectively. The observed line width obtained from the co-added spectra is 38±10 km s^{-1} (FWHM = 4200±1800 km s^{-1}) which corresponds to a radius of 20±50 light days, for the virial production of 1.220 × 10^7 M⊙ in NGC 5548. To quantitatively investigate the origin of the narrow Fe line by the reverberation mapping method, we compare the observed light curves of Fe Kα line with the predicted ones, which are obtained by convolving the continuum light curve with the transfer functions in a thin shell and an inclined disk. The best-fit result is given by the disk case with i = 30° which is better than a fit to a constant flux of the Fe K line at the 92.7% level (F-test). However, the results with other geometries are also acceptable (P > 50%). We find that the emitting radius obtained from the light curve is 25–37 light days, which is consistent with the radius derived from the Fe K line width. Combining the results of the line width and variation, the most likely site for the origin of the narrow iron lines is 20–40 light days away from the central engine, though other possibilities are not completely ruled out. This radius is larger than the Hβ emitting parts of the broad-line region at 6–10 light days (obtained by the simultaneous optical observation), and smaller than the inner radius of the hot dust in NGC 5548 (at about 50 light days).

Key words: galaxies: active – galaxies: individual (NGC 5548) – galaxies: Seyfert – quasars: emission lines – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

The neutral, photoionized iron K emission line commonly found in the X-ray spectra of active galactic nuclei (AGNs) can be decomposed into a narrow core around 6.4 keV and a broad redshifted component, though sometimes only one of them is present (Fabian et al. 2000; Yaqoob et al. 2001; Nandra et al. 1997, 2007). The broad, relativistic component could be modeled as being emitted from the vicinity of the central black hole and used to determine the parameters of the black hole (e.g., Brenneman & Reynolds 2006). An alternative explanation of this feature is the complex absorption origin (Miller et al. 2008). However, the origin of the narrow component is still unclear, but could be critical to understanding the central structure of AGNs. The narrow width (FWHM ∼ several thousand km s^{-1} or less; e.g., Yaqoob & Padmanabhan 2004) suggests an origin well outside the continuum producing region. One of the proposed sites is the putative “obscuring torus” (e.g., Nandra 2006) at ∼0.1–1 pc. The evaporation radius of the dust can be estimated by \( r = 1.3L_{\text{uv,46}}T_{1500}^{-1/2} \), where \( L_{\text{uv,46}} \) is the ultraviolet luminosity in units of 10^{46} erg s^{-1} and \( T_{1500} \) is the evaporation temperature in units of 1500 K. For NGC 5548, since \( L_{\text{uv,46}} \sim 0.01 \) and assuming \( T_{1500} = 1 \), the evaporation radius is about 0.1 pc. However, the broad emission lines have similar line widths, so the more compact broad-line region (BLR) is another possible location which cannot be ruled out simply. A BLR origin is supported by the quasi-simultaneous optical spectroscopic observation with Chandra observation of NGC 7213 (Bianchi et al. 2008), which shows consistent Fe K and Hβ line widths, and by the rapid \( N_H \) changes seen in several AGNs (Elvis et al. 2004; Puccetti et al. 2007; Risaliti et al. 2002), which require a BLR-like radius for the \( N_H \gtrsim 10^{23} \text{ cm}^{-2} \) absorbers. Seen from another angle, these absorbers must re-emit in Fe K.

The lag between the variation of the flux of the continuum and the line can be used to measure the location of an emission line region (Blandford & McKee 1982) and this “reverberation mapping” methodology has been applied to the optical and UV broad emission lines (BELs) with great success (Peterson et al. 2004). However, until now the 10% or greater error on the flux of the 6.4 keV Fe K line (compared with the usual 1%–5% error on the flux of BELs), and the low sampling
frequency of the X-ray observations, have made it hard to apply this method to determine lags for Fe K lines, especially on relatively short timescale expected (∼10 days for a BLR origin). For example, Chiang et al. (2000) found that the flux of the iron K line in NGC 5548 was consistent with being constant using the four simultaneous observations of ASCA and Rossi X-ray Timing Explorer (RXTE) within 25 days and another observation after about half a year. However, some response of the Fe K line to the continuum changes has been found no evidence for correlated variability between the line and continuum, comparable systematic long-term (≈3–4 years) decreases in the line and continuum were present in NGC 5548.

We report here on a series of seven sequential X-ray observations of NGC 5548 by Suzaku, spaced roughly weekly. This observing campaign was designed, among other goals, to constrain the flux of the iron line to about 10% in each observation. This allows us, for the first time, to apply the reverberation mapping technique to Fe K to try to distinguish different geometries of the Fe K emitting region. NGC 5548 is the source best studied by the optical reverberation mapping technique (e.g., Peterson & Wandel 1999) and so has the best determined radial structure. Therefore, it is easy to determine the relative location of the Fe K line emitting region. In previous observations, only the Fe Kα line was detected. As we will present in this paper, the Kβ line is also well detected in the Suzaku observations. Although very weak in some observations, Kβ is useful to constrain the ionization state of iron.

The iron line in NGC 5548 has been observed by several X-ray satellites: ASCA spectra suggested a relativistic broad iron Kα line in NGC 5548 with $\sigma = 340^{+130}_{-90}$ eV (68% error for four interesting parameters; Nandra et al. 1997) and $\sigma \sim 400$ eV (Chiang et al. 2000). However, less than two years later, only the narrow Kα line was detected in a Chandra observation with much higher energy resolution (38 eV versus 160 eV) but lower signal-to-noise ratio (S/N; Yaqoob et al. 2001). An XMM-Newton EPIC CCD observation confirmed the Chandra result (Pounds et al. 2003).

In Section 2, we describe the observations and the procedure of the data reduction. In this paper, we intend to investigate the origin of the Fe K line using the reverberation mapping method and the width of the line. Therefore, in Section 3, we first fit the spectra of each observation to determine the flux of the continuum and the iron line. We then fit the co-added spectra in Section 3.2 to determine the mean parameters, especially the width of the iron line. In Sections 4.2 and 4.3, we calculate the transfer functions in different geometries and investigate the possible emitting region of iron line. In Section 5.1, we discuss the possible origin of the iron line. In Section 5.3, we briefly discuss the implications of the intensity and the equivalent width of iron line. In Section 6, we give our conclusions. Throughout this paper we adopt the redshift of NGC 5548 obtained from 21 cm H1 measurements, i.e., $z = 0.017175$ (de Vaucouleurs et al. 1991). The errors quoted in this paper correspond to 90% confidence level ($\Delta \chi^2 = 2.706$; Avni 1976) if not otherwise specified.

### 2. OBSERVATIONS AND DATA REDUCTION

#### 2.1. Observations

During 2007 June to 2007 August, NGC 5548 was observed by the CCD X-ray Imaging Spectrometers (XIS 0, 1, and 3) in the 0.2–12 keV band (Koyama et al. 2007) and by the Hard X-ray Detector (HXD) in the 10–600 keV band (Takahashi et al. 2007) on Suzaku (Mitsuda et al. 2007) seven times for 28.9 ks–38.7 ks each. We denote these as observations 1–7. The details of the observations are summarized in Table 1.

#### 2.2. Data Reduction

Following the standard procedures outlined in the “Suzaku Data Reduction (ABCD) Guide (ver. 2)”11 we used the updated Charge Transfer Inefficiency (CTI) calibration (Suzaku CALDB 20081110) and screened the events using the xispi (Ftools 6.5) and xselect scripts provided by Suzaku team (we adopted the standard criterion in xis_event.sel and xis_nmf.sel),12 respectively.

X-ray spectra were extracted using xselect13 from all the XISs with a circular extraction region of radius 260 arcsec centered on NGC 5548 ($\alpha = 14^h17^m59.5^s, \delta = +25^\circ08'12.4''$; J2000). Background spectra were obtained from a larger annulus around the source (but avoiding the calibration sources on the corners of the chips). Response matrices (rmf) and effective area (arf) files were generated with the xismfgen14 and xissimarfgen15 (estepfile = dense and num_photon=300000, respectively). We then combined the spectra, background, rmf, and arf files from the two front-side illuminated CCDs, XIS 0 and 3, for each observation with addascaspec16 (we denote the combined spectra by “XIS03”). The spectra of XIS 1 are considered separately, as this detector uses a back-side illuminated CCDs.

#### Table 1

**Suzaku Observation Log**

<table>
<thead>
<tr>
<th>Sequence Number</th>
<th>Obs. ID</th>
<th>Start Date and Time</th>
<th>Exposure Time (ks)</th>
<th>3–10 keV Count Rate (10$^{-3}$ photons cm$^{-2}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>702042010</td>
<td>2007 Jun 18 UT 22:28:15</td>
<td>31.1</td>
<td>0.772</td>
</tr>
<tr>
<td>2</td>
<td>702042020</td>
<td>2007 Jun 24 UT 21:53:31</td>
<td>35.9</td>
<td>1.29</td>
</tr>
<tr>
<td>3</td>
<td>702042040</td>
<td>2007 Jul 08 UT 10:02:55</td>
<td>30.7</td>
<td>2.35</td>
</tr>
<tr>
<td>5</td>
<td>702042060</td>
<td>2007 Jul 22 UT 10:40:25</td>
<td>28.9</td>
<td>3.05</td>
</tr>
<tr>
<td>6</td>
<td>702042070</td>
<td>2007 Jul 29 UT 04:20:44</td>
<td>31.8</td>
<td>2.04</td>
</tr>
<tr>
<td>7</td>
<td>702042080</td>
<td>2007 Aug 05 UT 00:37:46</td>
<td>38.8</td>
<td>1.12</td>
</tr>
</tbody>
</table>

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11 http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/abc/
12 http://suzaku.gsfc.nasa.gov/docs/suzaku/analysis/xisrepro.xco,
http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/xis_event.sel,
http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/xis_nmf.sel
13 http://heasarc.nasa.gov/docs/software/lheasoft/ftools/xselect/index.html
14 http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/xismfgen.html
15 http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/xissimarfgen/
16 http://heasarc.gsfc.nasa.gov/heasoft/ftools/help/addascaspec.txt
NGC 5548 was detected by the silicon diode PIN instrument of the HXD, but below the sensitivity limit of the GSO crystal scintillator instrument. We downloaded the tuned non-X-ray background (NXB, ver. 2.0) files from the Suzaku Guest Observer Facility (GOF) and then merged the good-time interval (GTI) of the NXB with that of the screened event files to produce a common GTI using mgtime. Then the spectra of the source and the NXB were extracted by xselect using the common GTI. And the dead time of the source spectra was corrected by hxdttcor. Since the event rate in the PIN background event file is 10 times higher than the real background to suppress the Poisson errors, the exposure time of the spectra of NXB was increased by a factor of 10.

The cosmic X-ray background (CXB) was not taken into account in the NXB file, therefore we also added a CXB component in the spectral fitting using the model given by the ABC guide (see Section 7.3.3 of the guide). The response file ae_hxd_pinxinome3_20080129.rsp was used for observations 1–5, while the response file ae_hxd_pinxinome4_20080129.rsp was used for observations 6 and 7 due to the changes in instrumental settings of Suzaku during different observation epochs. The PIN spectra were multiplied by a constant cross-normalization factor of 1.16 to account for the differences in calibration between XIS and PIN.

![Figure 1. Best fit model (solid lines) and the added spectra of XIS03 (plus). The inset (a) is the residual of the spectra of XIS03 to the best fit of a single power law. The inset (b) is the added spectra of Mn Kα line of the calibration sources on XIS03.](image)

3. SPECTRAL FITTING

To perform the reverberation mapping calculation, we should first determine the flux of the continuum and the Fe K line. In order to avoid the influence of the complex absorption below 3 keV (Detmers et al. 2008; Steenbrugge et al. 2003), we only analyze the XIS spectra in 3–10 keV band. The warm absorber seen in the <3 keV spectra is presented by Krongold et al. (2010). In this paper, we will focus on the property and origin of the iron emission line. The result of a global fit to the entire Suzaku spectral band is very similar to that obtained in this paper, and it will be presented in a subsequent paper.

For each observation, we fitted the spectra of XIS03 simultaneously with the spectra of XIS 1 in XSPEC (ver. 12.4). Although both of the energy resolution and the effective area of XIS 1 are lower than XIS 0, 3 in the 4–10 keV band (the background level of XIS 1 is also higher than XIS 0, 3 in this band), it is still useful to reduce the error of the intensity of the Fe K line. We fixed the Galactic absorption column at $1.63 \times 10^{20} \text{ cm}^{-2}$ (Murphy et al. 1996), and fitted the spectra with a single power law. The continua were well described by a single power law except for the region of the iron Kα and Kβ lines around 6.4 keV and 7.0 keV, respectively (see Figure 1). Therefore, we added two Gaussian lines to describe these features. It is important to construct a self-consistent model to describe all the components of the continuum and theoretically predict the strength of the Fe K line, as in Murphy & Yaqoob (2009). However, this is not the purpose of this paper. Our purpose is only to simply model the Fe K line using a Gaussian line and determine the flux and width of it and then to perform the reverberation calculation. A Kα line is required by all the seven spectra (>6σ), while Kβ line is only required by four observations (>2σ for 1, 2, 4, and 7). The 90% upper limit of the flux of the Kβ line is determined in observations 3, 5, and 6. Since the Kβ line is weak, we fixed the width of Kβ to be the same as that of Kα. Fe Kβ line was also detected in other sources, e.g., NGC 2992 (Yaqoob et al. 2007) and Mrk 3 (Awaki et al. 2008). The detailed result of the fitting is given in Table 2, though we are mainly concerned about the flux of the continuum and the intensity of the Fe K line. Due to the weak reflection component in NGC 5548 (e.g., Pounds et al. 2003), if we simultaneously fit the continua in the XIS and PIN spectra of each observation using the pexrav model instead of the power-law model, the intensity of the Fe K line will systematically decrease by 10% for each observation (the strength of the reflection component $R \sim 0.2–1.5$). However, this change will not influence the reverberation mapping

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17 http://legacy.gsfc.nasa.gov/suzaku/data/background/pinnxb_ver2.0_tuned/
18 http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/watchout.html
result in Section 4.3, since it degenerates with the normalization of the transfer function (see the detail of the transfer function in Section 4.2). The PIN data are also not helpful to reduce the error of the flux of the Fe K line due to the additional uncertainty introduced by the reflection component and large error in the PIN spectra. The detailed discussion about the variation of the X-ray continuum and simultaneous UV/optical data will be presented in another paper.

### 3.1. Continuum Light Curve

Having fitted the spectra, we calculated the observed flux of the continuum in the 3–10 keV band. The resulting light curve is shown in Figure 3(a). To better sample the continuum light curve, we also utilized one observation of the continuum from the simultaneous Swift campaign. Since the observation times and the flux of other Swift data are quite similar to that of the Suzaku data, we will not include them in this paper. The details of the Swift campaign will be discussed in D. Grue et al. (2010, in preparation). Twenty eight observations of the continuum with Proportional Counter Array (PCA) on RXTE before the Suzaku campaign are also used, since we are looking for the lag between the variation of continuum and line. However, due to the short exposure time, we cannot determine the flux of the line in any of these additional observations. The details of the RXTE and Swift observations are summarized in Table 3.

### 3.2. Narrow Iron Lines

To determine the mean parameters of the Fe Kα and Kβ lines more accurately, especially the width of the line, we added the spectra from the seven observations together using addspec (the XIS03, XIS1, and PIN spectra were added separately and then fitted simultaneously). The net counts of the source in 3–10 keV band in the total XIS03 and XIS1 spectra are 160,349 and 75,332, respectively. The net counts of the source in the 12–35 keV band in the total PIN spectra is 22,243. We found that the XIS1 spectra could not provide any useful constraint on the width of the Fe K line, since the σ of the Gaussian line is pegged at 0 eV (the 90% upper limit is 30 eV). Therefore, we will only utilize the co-added XIS 03 and PIN spectra to determine the width of the Fe K line.

If we only fitted the co-added XIS03 spectra using the model in Section 3, i.e., a power law and two Gaussian lines, the width is σ = 50^+14_{-15} eV. However, since the weak reflection component could influence the width of the Fe K line, we then simultaneously fitted the co-added XIS 03 and PIN spectra using the pexrav model and two Gaussian lines. The derived parameters are given in Table 4, where the strength of the reflection component (R ~ 0.8) could explain the Fe K line. As shown in Figure 1, only a narrow iron line is clearly present in the spectra, with a width, σ = 38^+16_{-18} eV. This value is consistent with previous results: i.e., σ = 41^+32_{-25} eV obtained by HEG+MEG on Chandra (Yaqoob et al. 2001) and σ = 40^+40_{-40} eV (MOS) and 64^+24_{-24} eV (PN) obtained by XMM-Newton (Pounds et al. 2003).

Since the peak energies of the line and the parameters of the continua are somewhat different for each observation, we simultaneously fitted the spectra of all observations in XSPEC to test whether the line was broadened artificially in the co-added process. We required the width of line to be the same for all observations and kept other parameters free. The obtained width is only slightly smaller than that from the co-added spectra by about 2 eV, which implies the co-added method has not significantly broadened the width.

The width obtained by the co-added spectra is inconsistent with zero at 2.2σ and corresponds to FWHM= 4200 km s^{-1} and a radius of 5.2 × 10^{16} cm or 5.2 × 10^{3} r_{g} (r_{g} = GM/c^2), for the 6.71 × 10^{3} M_{⊙} black hole in NGC 5548 (Peterson et al. 2004). In Section 5.1, we will estimate the location of the emitting material of the line and discuss the origin of the line.

To test the presence of the broad, relativistic Fe Kα line found by ASCA, we tried the dinkline model in XSPEC to fit the Kα line. We fixed the inner and outer disk radii at 6r_{g} and 1000r_{g} (r_{g} = GM/c^2), respectively. The index of the power-law emissivity was frozen at −2.5 (the mean value obtained in
If we thaw the index, it will be pegged at 0 and the 90% upper limit is 4 \times 10^{-6} \text{ photons cm}^{-2} \text{ s}^{-1}.

Therefore, any broad component must be \(>5\) times weaker than the narrow component and we will not include this component in the following discussion.

We show the confidence regions for the peak energies of K$\alpha$ and K$\beta$ in Figure 2(a). The expected values of different iron ionization states (Palmeri et al. 2003; Mendoza et al. 2004; Yaqoob et al. 2007) are also shown. Since the peak energy may be influenced by the residuals in the energy scale calibration, we extracted the spectra of the $^{55}$Fe calibration sources on the RXTE and Swift Observation Logs.

Nandra et al. (1997). If we thaw the index, it will be pegged at the positive upper limit in XSPEC, i.e., the flux of the line is dominated by the outer disk and therefore it is not a disk line at all. It was found that the disk line model cannot describe the K$\alpha$ line alone, since $\chi^2$ was higher by 128 than for a narrow line with the same number of parameters. The same conclusion was also obtained by Yaqoob et al. (2001).

Next, we investigated the result if we fit the K$\alpha$ line with a disk line and a Gaussian line. Besides the constraint on the disk line model mentioned above, we also fixed the value of the inclination angle at 31 deg, which is the best-constrained value from the ASCA data (Yaqoob et al. 2001). We found the central value of the intensity of the disk line is pegged at 0 and the 90% upper limit is 4 \times 10^{-6} \text{ photons cm}^{-2} \text{ s}^{-1}.

Therefore, any broad component must be \(>5\) times weaker than the narrow component and we will not include this component in the following discussion.

We show the confidence regions for the peak energies of K$\alpha$ and K$\beta$ in Figure 2(a). The expected values of different iron ionization states (Palmeri et al. 2003; Mendoza et al. 2004; Yaqoob et al. 2007) are also shown. Since the peak energy may be influenced by the residuals in the energy scale calibration, we extracted the spectra of the $^{55}$Fe calibration sources on the corners of the CCDs and added them together (see the inset in Figure 1(b)). Using a Gaussian line to fit the Mn K$\alpha$ line, we found the peak energies are 5.892$^{+0.001}_{-0.003}$ keV and 5.893$^{+0.002}_{-0.001}$ keV for XIS03 and XIS1, respectively. The expected value of the Mn K$\alpha$ line is 5.895 keV. This result is well within the accuracy of...
Figure 2. Confidence region of the peak energies (a) and intensities (b) of Kα and Kβ obtained from the fitting of the co-added XIS03 and PIN spectra. The contours from inner to outer correspond to Δχ^2 = 1.00, 2.71, and 6.63 (68%, 90%, 99%), respectively. The crosses in (a) are the predicted values of the peak energies in different ionization states of iron. The lower and upper dashed lines in (b) correspond to the I(Kβ)/I(Kα) ratios of 0.12 and 0.20, respectively.

Figure 3. (a) Light curve of the flux of the continuum in the 3–10 keV band. The small error bar of the flux of the Suzaku observation is omitted. (b) The light curve of the flux of Kα line. The solid line in (b) is the result of the constant fitting (see the text in Section 4.1).

4. TIME VARIABILITY ANALYSIS

4.1. Fe Kα Line Light Curves

The light curve of Fe Kα line is shown in Figure 3(b) each being determined to ~10%. As Kβ is weak in some observations, we will only discuss the result for Kα below. As shown in Figure 3(a), the flux of the continuum changed strongly during the seven observations. The highest value (2.65 × 10^{−11} erg cm^{−2} s^{−1}, for observation 5) is about four times that of the lowest (6.89 × 10^{−12} erg cm^{−2} s^{−1}, for observation 1). However, perhaps due to the relatively large error, the flux of the line is consistent with being constant, χ^2_{min} = 3.05 (P = 80%) and the value of the corresponding line constant flux is 2.24 × 10^{−5} photons cm^{−2} s^{−1}.

A constant Fe Kα flux is the simplest solution to the Fe Kα light curve, and it requires the emitting region should be far from the central engine to smooth out the variation in short timescale. According to the result in Section 4.3 and Figure 6(b), it should be larger than 100 light days. However, as shown in Figures 1 and 2 in Markowitz et al. (2003), the presence of the variation of the Fe K flux in timescale shorter than 100 days indicates the emitting region must be smaller than 100 light days.
first calculate the transfer function for Fe K line. We will approach this problem in a different way. To do so we consider two cases: (1) a spherical region and (2) an inclined disk.

1. We assume the emitting material is spherically distributed around the center with an inner ($r_{\text{min}}$) and outer ($r_{\text{max}}$) radius. The transfer function in this model is then simply a constant between 0 and $2r_{\text{min}}/c$, and then decays to 0 at $2r_{\text{max}}/c$ (see Figure 4(a) and Peterson 1993).

2. For a thin disk, the general form of the transfer function is two-peaked (Welsh & Horne 1991). Figure 4(b) shows the result for different values of the inclination angle $i$ (the angle between the normal of the disk and the line of sight).

The shape of the transfer function depends on the form of the “responsivity” $\varepsilon(r)$ (see Figure 4(a)), which combines the effects of the distributions of the number density of clouds and the emissivity per cloud. We assumed that the responsivity is a power law $\varepsilon(r) \propto r^{-\alpha}$ and the normalization is adjusted to fit the observed light curve. The power-law form is simple and somewhat arbitrary. However, since we only consider the thin shell case (i.e., $\Delta r \ll r$, or equivalent to the locally optimized clouds model), the result is not sensitive to the detailed form of the responsivity nor the index of the power law (see Figure 6(a)). $\alpha = 3$ is adopted in the calculation in Section 4.3.

We could then obtain the predicted light curve of the line by convolving the transfer function with the light curve of the continuum flux. In the thin spherical shell and disk cases discussed in Section 4.3, it can be proved that the lag time, $\tau$, obtained by the CCF just corresponds to the radius of the emitting region, i.e., $\tau = r/c$ (Koratkar & Gaskell 1991).

### 4.3. Comparison with the Observed Light Curve

Since the observation data of the continuum are still too few to produce a complete light curve, we performed linear interpolation between data points to convolve the light curve with the transfer function.

We used the light curve of the continuum in 3–10 keV band in order to have precision measurements. Similar bands (e.g., 2–10 keV) have been adopted in the previous attempts to determine the lag between the variation of the continuum and the Fe K line (e.g., Markowitz et al. 2003, 2009), although only photons from above the ionization threshold can actually lead the emission of an Fe K photon. As shown in Figure 5, the flux in the 3–6 keV band is tightly and nearly proportionally correlated with the flux in the 8–10 keV band. Any possible effects due to rapidly changing $N_H$ (Risaliti et al. 2005) must therefore be small. As a result, the results of the following calculations will not be sensitive to the adopted energy band of the continuum. The change of the continuum slope is also related to the total amount of the ionization flux. However, this is a minor factor compared with the change of the normalization of the continuum. Specially, this effect should be even small for NGC 5548, since, e.g., Sobolewska & Papadakis (2009) showed that the continuum slope is nearly independent of the flux. We find the same lack of dependence (Table 2).

We fixed the width of the emitting region at 0.1 light days, substantially smaller than the likely radius of the Fe K emitting region, and varied $r_{\text{min}}$. After convolving the light curve of the continuum with the transfer functions in different geometries and $r_{\text{min}}$, we compared the predicted light curve of the line with the observed one to find the minimum value of $\chi^2$ (since the error on the flux is asymmetric, we conservatively adopt the larger one to calculate $\chi^2$). Figure 6(b) shows $\chi^2$ versus $r_{\text{min}}$. All the curves show pronounced minima (somewhat surprisingly, given the weak structure in the Fe K$\alpha$ light curve) and finally

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21 A similar approximation is used in reverberation mapping of AGNs (e.g., Peterson et al. 2002; Bentz et al. 2007).
decrease toward the result of the constant fitting (the horizontal dashed line in Figure 6(b)) with increasing $r_{\text{min}}$, as the result of the significant smoothing effect with large $r_{\text{min}}$. The values of minimum $\chi^2$ in the spherical thin shell case and disk case with $i = 15^\circ$ and $i = 30^\circ$ are well below that of the constant fitting, and we will only discuss these three cases below. With the smallest value of $\chi^2$, the best-fitting light curve in the disk with $i = 30^\circ$ is improved at 92.7% level compared with the constant fitting. We show the predicted light curves corresponding to the minima of $\chi^2$ in these three cases in Figure 7. Due to the few data points, we cannot tightly constrain the inclination angle. Except for the disk case with $i = 15^\circ$, the positions of the minimum $\chi^2$ in the spherical case ($27_{-22}^{+27}$ light days) and the disk case with $i = 30^\circ$ ($37_{-26}^{+22}$ light days) are similar, and they are smaller than the inner radius of the dust ($47_{-53}^{+18}$ light days, see the discussion in Section 5.1). The value of the best-fitting $r_{\text{min}}$ in the disk case with $i = 15^\circ$ is $61_{-50}^{+54}$ light days, which is beyond the inner radius of the dust of NGC 5548 (such optically thick region will significantly absorb the photons of Fe K lines) and only marginally consistent with the small tail of the 90% confidence intervals for both quantities. The disk case with $i = 30^\circ$ and the spherical case are consistent with the width of the co-added Fe Kα line. Combining the above results, we conclude that the origin of the narrow iron line in NGC 5548 is likely to be $\sim 20–40$ light days away from the continuum source, for the geometries considered. However, the other possible origins are not completely ruled out due to the incompleteness of the light curves, our model-dependent method, and the sizeable error on the width of the Fe K line.

Since NGC 5548 is one of the best-studied AGNs with reverberation mapping, the locations of the BELs are well-determined, especially for the Hβ line. The lag between the flux of Hβ line and the continuum varies from 6.5 light days to 26.5 light day depending on the luminosity of the continuum (Bentz et al. 2007; Cackett & Horne 2006). Since the correlation between the lag time and the continuum flux is more significant than the correlation between the lag time and the width of Hβ line (Bentz et al. 2007), and the broad component of the Hβ line is weak during the Suzaku campaign, we will utilize the continuum flux to predict the radius of the Hβ line region.

From the simultaneous optical spectra of NGC 5548 from FLWO FAST spectrograph (2007 June 19–23), we measured

$$\sigma = 0.55 \pm 0.05 \text{ cm/s}$$

$$\sigma = 0.55 \pm 0.05 \text{ cm/s}$$

Figure 5. Top panel shows the correlation between the flux in the 3–6 keV band and that in the 8–10 keV band of all seven observations. The solid line is the best-fitting straight line across the origin. The error bars of the fluxes are omitted, since they are smaller than the symbols. The bottom panel shows the ratios between the flux in the 8–10 keV band and that in the 3–6 keV band.

5. DISCUSSION

5.1. Location of the Fe K Emitting Region

Assuming the geometry and dynamics of the emitting region of the Fe K line are the same as that of the Hβ line, and using the virial relation for the Hβ line, $\sigma^2 r / G = 1.220 \times 10^7 M_\odot$ (Peterson et al. 2004), the radius of the Fe K emitting region can be derived using the Fe Kα width, $\sigma$, obtained in Section 3.2. The derived radius using the width obtained by the co-added XIS03 and PIN spectra is $20_{-10}^{+50}$ light days.22

In Figure 8, we plot the line width size against $r_{\text{min}}$ from the reverberation analysis (Figure 6(b)) for both the spherical thin shell case and the disk case with $i = 30^\circ$ with 90% confidence intervals for both quantities. The disk case with $i = 30^\circ$ and the spherical case are consistent with the width of the co-added Fe Kα line. Combining the above results, we conclude that the origin of the narrow iron line in NGC 5548 is likely to be $\sim 20–40$ light days away from the continuum source, for the geometries considered. However, the other possible origins are not completely ruled out due to the incompleteness of the light curves, our model-dependent method, and the sizeable error on the width of the Fe K line.

22 Since the virial production is an observed quantity and the radius derived from width will be compared with that also obtained from the reverberation mapping method, no additional geometry factor is required.

23 The calibration residual in the width of Mn Kα line derived in Section 3.2 ($12_{-3}^{+2} \text{ eV}$ and $16_{-3}^{+4} \text{ eV}$ for XIS03 and XIS1, respectively) is partly due to the systematic error on the calibration of the non-Gaussian response function of XIS (Koyama et al. 2007). The energy resolution at the center of the CCD chip is also slightly better than that at the corner, but this difference is smaller than the systematic error on the calibration. Therefore, the true width of the Fe K line could be smaller than the observed one by a few eVs due to the above factors. However, these effects could not be accurately corrected simply.
Figure 6. (a) Comparison with different values of $\alpha$ in the spherical case. $\alpha = 2$ (blue), $\alpha = 3$ (red), and $\alpha = 4$ (green). Since the original curves are nearly identical, the curves of $\alpha = 2$ and $\alpha = 4$ are vertically shifted by $-0.5$ and $0.5$, respectively. (b) The curves of $\chi^2$ with different $r_{\text{min}}$ for spherical and disk cases. Spherical (black), disk $i = 15^\circ$ (blue), $i = 30^\circ$ (red), $i = 45^\circ$ (green), and $i = 60^\circ$ (yellow). The horizontal dashed line is the $\chi^2$ of the constant fitting (see the text). (c) Enlarged plot of (b). The error bar at the bottom is the 90% confidence interval inferred from the line width obtained by the simultaneous fitting of all spectra (see Figure 8).

Figure 7. Comparison between the observed and predicted light curve of the flux of the line with the minimum of $\chi^2$ in different cases, i.e., (a) spherical case, (b) disk case with $i = 15^\circ$, and (c) disk case with $i = 30^\circ$.

Figure 8. Relationship between $\sigma$ of the line and the radius of the emitting region inferred from the black hole mass. The vertical dashed and solid lines correspond the central value and the 90% confidence intervals of the line width obtained by the co-added XIS 03 and PIN spectra, respectively. The horizontal lines correspond to the 90% confidence intervals of the emitting region inferred from the light curve in the spherical case (solid) and the disk case with $i = 30^\circ$ (dashed, see Figure 6(c)).

The monochromatic flux at 5100 Å and used this flux to estimate the radius of the Hβ emitting region at the time of the Suzaku campaign. After calibration with a standard star, the optical spectra were put on an absolute calibration scale assuming a constant flux of $F(\text{OIII} 5007)_{\text{standard}} = 5.58 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$ (Peterson et al. 1991) and found the monochromatic flux at 5100 Å, $F(5100 \text{ Å})_{\text{observed}} = 5.13 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}$. For the aperture size of 5 arcsec $\times$ 7.5 arcsec, the contribution of the host galaxy at 5100 Å is $4.47 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}$ (Bentz et al. 2006). To account for the effect of the aperture...
and the difference between telescopes, the flux measured by FLWO should be converted by the coefficients given in Peterson et al. (2002), i.e., $F(5100 \, \text{Å})_{\text{true}} = \varphi F(5100 \, \text{Å})_{\text{observed}} - G$.

We averaged the results using the different coefficients (i.e., $\varphi$ and $G$) determined in years 8 and 9–13 of the campaign (see details in Peterson et al. 2002), and then excluded the flux of the host galaxy ($4.47 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$, Bentz et al. 2006). The final 5100 Å flux of the AGN in NGC 5548 is $(1.7 \pm 0.7) \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ during the Suzaku campaign. With the relation between the emitting region of Hβ and line and the intensity of the Fe K line and $N_H$ or the abundance of iron is quite nonlinear, and the intensity of the Fe K line also significantly depends on the geometry of the emitting region and the observing angle. Since the detailed investigation of the geometry, $N_H$, and the abundance of the emitting region of Fe K lines is much beyond the scope of this paper, we will not further discuss the constraints obtained from the intensity and the equivalent width of the Fe K lines.

5.3. Theoretical Intensity of the Fe Line

The intensity and the equivalent width of the iron line can be estimated theoretically (Krolik & Kallman 1987; Yaqoob et al. 2001). We found the column density $N_H > 10^{23}$ cm$^{-2}$ is required to produce the observed intensity and the equivalent width of the Fe Kα line in our Suzaku observations. However, as pointed out by Miller et al. (2009) and Yaqoob et al. (2010), due to the self-absorption effect and the Compton scattering, for $N_H > 10^{23}$ cm$^{-2}$, the relation between the intensity of the Fe K line and $N_H$ or the abundance of iron is quite nonlinear, and the intensity of the Fe K line also significantly depends on the geometry of the emitting region and the observing angle. Since the detailed investigation of the geometry, $N_H$, and the abundance of the emitting region of Fe K lines is much beyond the scope of this paper, we will not further discuss the constraints obtained from the intensity and the equivalent width of the Fe K lines.

6. CONCLUSIONS

We analyzed the iron Kα and Kβ lines in spectra of NGC 5548 obtained by Suzaku XIS and summarize our results as follows.

1. The iron Kα line was well detected (> 6σ) in all seven observations and the Kβ line was also detected (> 2σ) in four observations (1, 2, 4, and 7).

2. Only a narrow iron line was found in the spectra. The line width obtained by the added spectra is 38$^{+6}_{-16}$ eV, which is consistent with the results of Chandra and XMM-Newton. Assuming the same virial relation as that of the Hβ line, this width corresponds to a radius of 20$^{+50}_{-10}$ light days. Any relativistically broadened disk line must be a factor of 5 weaker than the narrow component in flux at 90% confidence level.

3. We compared the observed peak energies and intensity ratios of Kα and Kβ lines with the expected value and found they are consistent with the low ionization states of iron, i.e., lower than Fe xiii, at the 99% confidence level.

4. The Fe Kα line is consistent with being constant over the 50 days of the Suzaku campaign, although the 3–10 keV continuum varies by a factor of 4. It is shown that a location at > 100 light days is consistent with the data (see the discussion in Section 4.3 and Figure 6(b)), but this is not a unique result.

5. To further access the location of the iron lines using the light curve, we calculated the transfer functions in spherical and disk geometries, and compared the predicted light curves with the observed one. The value of $\chi^2$ is smallest in the disk case with $i = 30^\circ$, which is better than the constant fitting at the 92.7% level. The spherical thin shell case is also acceptable ($P = 81\%$). The inferred emitting radii are $27^{+22}_{-17}$ light days in the spherical case and $37^{+18}_{-13}$ light days in the disk case with $i = 30^\circ$.
the disk case with $i = 30^\circ$, which are consistent with that obtained from the width of iron lines.

6. Combining the Suzaku constraints, the most likely origin of the narrow iron lines is about 20–40 light days away from the central engine, i.e., the outer part of BLR ($5.2 \times 10^3$–$1.0 \times 10^4$ $r_g$). However, we could not completely rule out other possible origins.

The approaches used in this paper offer a valuable tool for determining the size and structure of the inner regions of AGNs, although we stress again this method is model dependent. The constraint on the emitting region of the narrow Fe K line obtained by the width will be greatly improved by upcoming calorimeters, which have >10 times better energy resolution, of only a few eV. If future X-ray satellites (e.g., Astro-H, IXO, and Gen-X) with larger effective area could reduce the error of the flux of the Fe K emission line by even a factor of 2, then it will be possible to distinguish different geometries from the constant flux fitting. Higher sampling frequency campaign, preferably over a longer baseline, is also desirable to obtain a cross-correlation function with a quality comparable to or better than current optical observations.

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REFERENCES

Mitsuda, K., et al. 2007, PASJ, 59, S1