Fe K LINE COMPLEX IN THE NUCLEAR REGION OF NGC 253

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ABSTRACT

A bright, nearby edge-on starburst galaxy, NGC 253, was studied using the Suzaku, XMM, and Chandra X-ray observatories. With Suzaku and XMM we detected complex line structure of Fe K, which is resolved into three lines (Fe i at 6.4 keV, Fe xxv at 6.7 keV, and Fe xxvi at 7.0 keV) around the center of NGC 253. Especially, the Fe i and Fe xxvi lines are the first clear detections, with a significance of >99.99% and 99.89% estimated by a Monte Carlo procedure. Imaging spectroscopy with Chandra revealed that the emission is distributed in ~60 arcsec$^2$ region around the nucleus, which suggests that the source is not only the buried active galactic nucleus. The flux of highly ionized Fe lines can be explained by the accumulation of 10–1000 supernova remnants that are the result of high star-forming activity, while the Fe i line flux is consistent with the fluorescent line emission expected with the molecular clouds in the region.

Key words: galaxies: individual (NGC 253) – galaxies: ISM – galaxies: starburst – galaxies: star formation – X-rays: galaxies

1. INTRODUCTION

X-ray emission from the central region of a starburst galaxy is known to be complex because of blending of various kinds of point sources and diffuse emission. Although point-source emission typically dominates the hard band, in some starburst galaxies including NGC 253, the emission line from He-like Fe xxv is observed, suggesting the existence of a high-temperature plasma (e.g., Pietsch et al. 2001; Boller et al. 2003; Ranalli et al. 2008). Supernova remnants (SNRs), associated with starburst activity, are considered to be a candidate of the origin. Moreover, two of the galaxies (NGC 6240 and M82) exhibit Fe i fluorescent line (Boller et al. 2003; Strickland & Heckman 2007). The coexistence of highly ionized and neutral Fe lines suggests the coexistence of hot and cold gases. Thus, this complex Fe K line structure is informative on the origin of the emission and the gas structure of starburst galaxies. The origin of the neutral line is, however, still poorly known.

NGC 253 is a nearby bright edge-on starburst galaxy with a star formation rate of 1.4–9.5 $M_\odot$ yr$^{-1}$ (Grimm et al. 2003). Its large apparent diameter makes it a suitable target for studying the spatial distribution of emission features. Chandra suggested that the X-ray emission in the nuclear region is composed of a low-temperature thermal plasma and a heavily absorbed hard component that is expressed by a power law plus emission from a photoionized plasma emitting Fe iv–Fe xv and Fe xxv (Weaver et al. 2002). The hard component is interpreted as a buried active galactic nucleus (AGN; Müller-Sánchez et al. 2010). The spectrum around the nuclear region could be modeled with three-temperature thin thermal plasmas including a high (~6 keV) temperature plasma responsible for the Fe xxv line (Pietsch et al. 2001).

In this Letter, we report on the study of the nuclear region of NGC 253 using Suzaku and Chandra, with a particular focus on the Fe line complex. Suzaku has a good energy resolution to resolve the Fe line complex with a low background, while a sub-arcsecond spatial resolution of Chandra enables us to argue spatial distribution. We also show results by XMM-Newton as a complementary analysis. Throughout this Letter, we adopt a distance to NGC 253 of 3.4 Mpc (Dalcanton et al. 2009) corresponding to 16 pc arcsec$^{-1}$. We assume the solar abundance tabulated by Anders & Grevesse (1989). HEAsoft version 6.11, SAS 10.0.0, CIAO 4.3, and XSPEC 12.7.0 were used for data reduction and spectral analysis. For all fitting processes, we adopted C-statistics and binned spectra so that each bin contains >10 counts after a background subtraction. We quote an error as a 90% significance level of a single parameter in all tables, determined by Monte Carlo simulations and most of the errors are consistent with those obtained by AC-statistic of 2.7.

2. OBSERVATIONS AND DATA REDUCTION

NGC 253 was observed by Suzaku (seq:805018010) with an exposure time of 101 ks. We analyzed only XIS–FI (XIS0 and XIS3), which has a lower background than XIS–BI (XIS1) at >5 keV to avoid a systematic uncertainty associated with a simultaneous fitting of different sensors. The Redistribution Matrix Files (RMFs) and Ancillary Response Files (ARFs) were created with the xisrmfgen and xissimarfgen ftools (Ishisaki et al. 2007), respectively. Since the bright region is within several tens of arcseconds, which is much smaller than the Suzaku point-spread function (PSF; 1.8 as a half-power diameter), we assume the source to be a point source when creating the ARF files. The accumulation of dark Earth observations was used to estimate the non-X-ray background (NXB) spectra, via the xisnxbgen ftool (Tawa et al. 2008). We subtracted the NXB, the dominant background above 5 keV, but not the X-ray background, which was evaluated by an offset observation next to our field as to be less than 3% of the flux in R0. The spectra and responses of XISO and XIS3 were merged using the ftools mathpha, marfmf, and addrmf.

We utilized PN data from two XMM observations (ObsIDs:0125960101 and 0152020101) with the effective exposure time of 31 and 54 ks after removing flared time intervals which is over 0.35 counts s$^{-1}$ above 10 keV. RMF and ARF files were made by the SAS rmfgen and arfgen tools. We extracted the background from a source-free region.

The object was also observed by Chandra three times with a net exposure time of 14 ks (seq:600114), 44 ks (seq:600093), and 83 ks (seq:600305), respectively. We analyzed the level 2 data.


**Figure 1.** Images taken by Suzaku XIS3 (left), XMM PN (middle), and Chandra ACIS (right) in 4.0–10 keV. The red ellipse and magenta “X” correspond to an optical disk and the center of the Chandra image. Green circles and ellipses are regions used for extracting spectra.

**Figure 2.** Spectra with residuals in 5.0–8.0 keV of Suzaku FI (left), XMM PN (middle) from R0, and Chandra ACIS from (R1 + R2). The regions are defined in Figure 1. Each residual panel indicates that to the model of power-law, (ii) power-law + gaussian, (iii) power-law + 2gaussian and (iv) power-law + 3gaussian. The power-law continuum was determined by excluding 6.3–7.1 keV to avoid the contamination from Fe K emission lines.

**Chandra ACIS-S** event data. We used the merged data of three observations without any good-time-interval filtering because the background count rate is always <6.5% of the source in 5.0–8.0 keV. RMFs and ARFs were created using the CIAO mkacisrmf and mkwarf tools. We extracted the background from a source-free region.

3. ANALYSIS AND RESULTS

3.1. Neutral, He-like, and H-like Fe K Lines with Suzaku and XMM

Spectra taken with Suzaku were extracted from a circular region with a radius of 2.3, indicated as R0 in the left panel of Figure 1. The center of R0 corresponds to the peak position of the Suzaku 4.0–10.0 keV image. The size of R0 was optimized to realize the largest number of photons avoiding other disk-origin components and anomaly columns in the XIS0 detector below the nuclear region.

As shown in the left panel of Figure 2, complex Fe K line structure was detected from the Suzaku spectrum as large residuals to a power-law continuum model. The continuum was determined in 5.0–8.0 keV but excluding 6.3–7.1 keV to avoid Fe K emission lines. We added Gaussian emission line models one by one. The line width was fixed to 0. Fitting was significantly improved by each step. The best-fit line center, equivalent width (EW), and flux, along with their errors are summarized in Table 1. We considered only the error of line flux in estimating the error of the EW. A systematic error in flux due to PSF modeling is bracketed by comparing two ARFs: one for a point source and one for a uniformly extended source. The difference, ∼10%, was smaller than the statistical error. Suzaku XIS achieved an energy scale accuracy better than

| Region | Parameters | Neutral Fe | Fe xxv | Fe xxvi |
|--------|------------|------------|--------|--------|
| Suzaku | Energy (keV) | 6.36 ± 0.03 | 6.67 ± 0.02 | 6.96 ± 0.05 |
| R0 | Flux $^b$ | 3.8$^{+1.1}_{-1.0}$ | 8.4$^{+1.2}_{-1.1}$ | 2.3$^{+0.9}_{-1.2}$ |
| | EW (eV) | 84$^{+25}_{-22}$ | 220$^{+31}_{-29}$ | 60$^{+25}_{-31}$ |
| XMM | Energy (keV) | 6.49 ± 0.02 | 6.72 ± 0.01 | 6.99 ± 0.03 |
| R0 | Flux $^b$ | 3.8$^{+1.0}_{-0.8}$ | 8.0 ± 0.9 | 2.1$^{+0.8}_{-0.9}$ |
| | EW (eV) | 77$^{+16}_{-07}$ | 189 ± 21 | 52$^{+20}_{-22}$ |
| Chandra | Energy (keV) | 6.40 (fix) | 6.66$^{+0.05}_{-0.06}$ | 6.97 (fix) |
| R1 | Flux $^b$ | <0.9 | 2.1 ± 1.2 | <1.1 |
| | EW (eV) | <33 | 253 ± 145 | <91 |
| R2 | Energy (keV) | 6.45$^{+0.19}_{-0.09}$ | 6.64$^{+0.04}_{-0.01}$ | 6.97 (fix) |
| | Flux $^b$ | 1.2 ± 1.1 | 4.8$^{+1.4}_{-1.1}$ | <0.8 |
| | EW (eV) | 86 ± 79 | 617$^{+80}_{-141}$ | <59 |
| R1+R2 | Energy (keV) | 6.43$^{+0.20}_{-0.08}$ | 6.64$^{+0.02}_{-0.03}$ | 6.95$^{+0.13}_{-0.12}$ |
| | Flux $^b$ | 1.7$^{+1.3}_{-1.3}$ | 7.1$^{+1.3}_{-0.9}$ | 1.7 ± 1.2 |
| | EW (eV) | 75$^{+49}_{-45}$ | 427$^{+90}_{-84}$ | 82 ± 58 |
| P1 | Energy (keV) | 6.46$^{+0.20}_{-0.07}$ | 6.65 ± 0.04 | 6.97 (fix) |
| | Flux $^b$ | 0.8$^{+0.7}_{-0.4}$ | 1.9$^{+1.0}_{-0.6}$ | <0.9 |
| | EW (eV) | 176$^{+154}_{-138}$ | 662$^{+248}_{-209}$ | <73 |

**Notes.**

$^a$ Energy center at the rest frame.

$^b$ Photon flux in the unit of $10^{-6}$ photons s$^{-1}$ cm$^{-2}$. 


et al. (2009) to calculate a significance of these lines. In this process, we evaluated the reduction in the C-statistic (29.9 for Fe i and 11.4 for Fe xxvi) after adding a line with the energy center range restricted to 6.3–6.5 keV for the Fe i line and 6.87–7.07 keV for the Fe xxvi line. The two lines were added individually. We conducted 10,000 Monte Carlo simulations for the Fe i and Fe xxvi lines with the same exposure and binning as the observation. The fraction of simulation that improved the C-statistic by 29.9 and 11.4 is 0 and 1 × 10^{-3}, respectively. Therefore, the significance of the detection of Fe i and Fe xxvi is >99.99% and 99.89%, respectively. This is the first clear detection of the Fe i and Fe xxvi lines in NGC 253.

We also extracted a spectrum from R0 by XMM as a complementary analysis. We found the same complex Fe K lines as observed with the Suzaku observation. As described above, the observed Fe K complex is unlikely to be explained by the AGN alone. In this section, we conducted imaging analysis to demonstrate the spacial distribution of this structure. Figure 3 shows the Chandra narrowband line flux image for the Fe xxv (6.6–6.8 keV) line. Contribution of the continuum was subtracted from the images in the following way. We simply assumed that the continuum above 5 keV is expressed by a single power law with the same photon index (2.0) in the whole region. The contribution from the continuum in 6.6–6.8 keV is calculated pixel by pixel using the photon index and the counts in 5.0–6.0 keV where no line feature exists. The assumption of a uniform photon index is rather crude because this can be applied for only the same spectrum properties. We also confirmed that the following results did not change with a different assumption of photon indices (1.0 and 4.0). In R1, a heavily absorbed non-thermal component from the buried AGN instead of a high-temperature plasma dominates the hard band above 3 keV. Despite poor statistics, the map suggests that the line emission is not concentrated in R1, i.e., the location of the buried AGN. In contrast, two bright regions of Fe xxv line are found in P1 and P3 defined in Figure 3.

We also extracted the line flux image for the neutral Fe K line. However, the statistics are too poor to do any analysis. Hence, we focus on the Fe xxv. To confirm the strong line emission in P1 and P3, we extracted spectra from four regions as indicated in Figure 3 denoted as P1, P2, P3, and P4. P1 and P4 are circles with a radius of 1″′ whose center is at the peak position of 1.5 × 3″. P1 and P3 include the peak position while P2 and P4 are selected from darker areas for comparison. P1 shows a strong line feature, while no line feature is found in P4. The resulting line fluxes in P1 are shown in Table 1. Of the observed total Fe i and Fe xxv lines, ~50% and 30% are emitted only from P1 as shown in the left panel of Figure 4. P2 and P3 have the same continuum flux but the resulting line flux of P3 for Fe xxv is two times larger than that of P2.

The coordinates of peak pixel centers in P1 and P3 are (α2000, δ2000) = (00h47m33s20, −25°17′17″2) and (00h47m33s01, −25°17′19″7), respectively. These are coincident with the peak positions of 1.3 mm continuum in the radio observation (Sakamoto et al. 2011) to within the position resolutions. The 99% uncertainty of absolute X-ray position by Chandra is 0′′8, while the beam size of the radio observation is 1′′1 × 1′′1. Thus, the Fe xxv line shows a clear association with the two peaks of
molecular clouds. P1 is the most luminous in mid-infrared and is suggested to be a super star cluster (Keto et al. 1999). P3 is the brightest in the 1.3 mm radio continuum and features the wide-band spectrum in 0.8–10 keV. Magenta, red, and green lines indicate thin thermal plasmas and the neutral Fe K line.

3.4. Wide-band Spectrum Fitting of the P1 Region

To extract physical parameters we fitted the wide-band spectra (0.8–10 keV) of P1, where the highest line flux was confirmed. We adopted two-temperature thermal plasmas in collisional ionization equilibrium plus a Gaussian whose centroid is 6.4 keV as the neutral Fe K line. One plasma represents highly ionized Si and S emission lines and the other makes up for continuum above 3 keV and the Fe xxv emission line. The spectrum with the best-fit model is plotted in Figure 4. The abundance is fixed at solar values. The spectrum is well represented with a C-statistic/dof of 132/95. The temperature of the higher-temperature plasma is 2.5$^{+0.3}_{-0.5}$ keV. This plasma is responsible for the Fe xxv and Fe xxvi lines. The unabsorbed luminosity, thermal energy, and total iron mass of the higher-temperature plasma are calculated to be (8.6 $\pm$ 1.4) $\times$ 10$^{38}$ erg s$^{-1}$, 5.4$^{+0.6}_{-0.5} \times$ 10$^{52}$ erg, and 20 $\pm$ 2 $M_{\odot}$, respectively. The unabsorbed luminosities of the Fe i and Fe xxv lines in P1 are also calculated to be 1.2$^{+1.0}_{-0.9} \times$ 10$^{37}$ and 2.7$^{+1.2}_{-1.5} \times$ 10$^{37}$ erg s$^{-1}$. Note that P1 has a radius of 24 pc and a spherical volume of 5.8 $\times$ 10$^4$ pc$^3$.

4. ORIGIN OF THE EMISSION LINES

In this section, we discuss the origin of the neutral Fe i, ionized Fe xxv, and Fe xxvi lines. This line structure likely extends to the R2 region, i.e., the central 8" corresponding to $\sim$130 pc in the nuclear region of NGC 253. However, we focus on the very compact P1 region with a radius of 24 pc, which shows the most luminous line structure. We calculate the contribution from (1) point sources such as cataclysmic variables (CVs), active binaries, and high-mass X-ray binaries (HMXBs), (2) SNRs, and (3) cold molecular clouds. Candidate (1) would produce all three lines, while (2) and (3) would only be responsible for the ionized lines and the neutral lines, respectively.

4.1. Point Sources

CVs and active binaries are bright point sources that emit Fe lines with typical luminosities of $L_{2-10keV} \sim 10^{31}$–$10^{32}$ erg s$^{-1}$ and $L_{2-10keV} < 10^{31}$ erg s$^{-1}$, respectively. The luminosity in P1 corresponds to $10^{7-8}$ sources, or a number density of $\sim$100–1000 pc$^{-3}$. We can also estimate the number density from line flux of CVs which are relatively luminous compared to active binaries. The typical luminosity of the Fe i line is on the order of $10^{29-30}$ erg s$^{-1}$ (Ezuka & Ishida 1999), which leads to the large number $10^4$–$10^5$ sources and a number density of $\sim$500–5000 pc$^{-3}$. The number density of CVs and active binaries are both $10^{-5}$–$10^{-2}$ pc$^{-3}$ in the Galaxy (e.g., Rogel et al. 2008; Favata et al. 1995). Even at the Galactic center, the expected number density of CVs is on the order of $10^{-2}$–$10^{-1}$ pc$^{-3}$, assuming that their number density can be scaled from the stellar density (Muno et al. 2003). Therefore, the contribution of these point sources seems low.

4.2. SNRs

SNRs likely make the biggest contribution as a diffuse plasma. The luminosity and thermal energy of young or middle-aged SNRs which contribute to highly ionized Fe lines in the LMC are $10^{36}$–$10^{37}$ erg s$^{-1}$ and $10^{51}$–$10^{52}$ erg, respectively (Hughes et al. 1998). Both the luminosity and thermal energy of the higher-temperature plasma of NGC 253 correspond to about 100–1000 and 10–100 young or middle-aged SNRs, respectively. We also estimated the number of SNRs using the observed Fe mass ($20 \pm 2 M_{\odot}$) and Fe mass ejection per one Type II SN ($8.4 \times 10^{-2} M_{\odot}$; Iwamoto et al. 1999). The resultant number of SNRs is about 240 $\pm$ 20 which is consistent with the estimated value from the luminosity. This suggests that the very dense massive star cluster in P1 exists, which is consistent with the results of the mid-infrared observations.

4.3. Molecular Clouds

Molecular clouds that are irradiated by surrounding X-ray sources would emit a fluorescent Fe i line. We assume that the incident X-ray is photoelectrically absorbed by the molecular gas that subtends an angle $\Delta\Omega$ seen from the continuum source.
The line flux of the Fe K line can be estimated as

\[
I_{6.4\,\text{keV}} = \left(\frac{\Delta V}{4\pi}\right) \epsilon \int_{7.1\,\text{keV}}^{\infty} dE \int \left(\frac{n_{\text{Fe}} \sigma_{\text{Fe}}(E)}{N_{\text{H}}}ight) F(E),
\]

where \(\epsilon\), \(n_{\text{Fe}}\), \(\sigma_{\text{Fe}}(E)\), and \(F(E)\) indicate the fluorescence yield of Fe K line (\(\epsilon = 0.34\)), the density of the molecular gas, the photoelectric cross-section, and the X-ray source intensity, respectively. Assuming a thermal bremsstrahlung spectrum for the continuum source, the X-ray source intensity, \(F(E) \propto \exp(-E/k_B T)\), can be determined in the 6.0–7.5 keV band. The Fe column density is written as \(\int n_{\text{Fe}} ds = Z_{\text{Fe}} N_{\text{H}}\), where \(Z_{\text{Fe}}\) and \(N_{\text{H}}\) represent the elemental abundance of iron to hydrogen and the column density of the required molecular gas, respectively. The photoelectric cross-section of Fe above 7.1 keV is approximated as \(\sigma_{\text{Fe}}(E) = 3.8 \times 10^{-20}(E/7.1\,\text{keV})^{-2.58}\) cm\(^2\) as described in Nobukawa et al. (2008). Substituting these values, we obtain

\[
N_{\text{H}} = (1.0^{+0.9}_{-0.3}) \times 10^{24} \left(\frac{\Omega}{2\pi}\right)^{-1} \text{cm}^{-2}. \tag{2}
\]

The solid angle \(\Omega = 2\pi\) corresponds to the case where the X-ray sources are distributed entirely behind the molecular gas. This column density was consistent with the molecular clouds observed in the radio observation (Sakamoto et al. 2011) to within the statistical errors. Thus, the observed Fe K line flux is explained by the emission from the NGC 253 nucleus and the dense molecular clouds in the nuclear region.

5. CONCLUSIONS

Suzaku and XMM observations revealed complex Fe K line structure in the nuclear region of NGC 253 and resolved it into Fe i, Fe xxv, and Fe xxvi lines. Chandra demonstrated that the emission is concentrated mostly in the \(\sim 60\) arcsec\(^2\) nuclear region, but is not localized at the position of a buried AGN. The Fe xxv line shows an association with molecular clouds.

The complex Fe K line can be explained by a combination of 10–1000 SNRs and a fluorescent line from molecular clouds (\(N_{\text{H}} \sim 10^{24}\) cm\(^{-2}\)).

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