X-Ray Halo around the Spiral Galaxy NGC 4631 Observed with Suzaku

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Abstract

A Suzaku observation of the edge-on spiral galaxy NGC 4631 confirmed its X-ray halo extending out to about 10 kpc from the galactic disk. The XIS spectra yielded the temperature and metal abundance for the disk and the halo regions. The observed abundance pattern for O, Ne, Mg, Si, and Fe is consistent with the metal yield from type II supernovae, with an O mass of about $10^5 M_\odot$ contained in the halo. These features imply that metal-rich gas produced by type II supernova is brought into the halo region very effectively, most likely through a galactic wind. The temperature and metal abundance may be affected by charge exchange and dust. An upper limit for the hard X-ray flux was obtained, corresponding to a magnetic field higher than 0.5 \( \mu \)G.

Key words: galaxies: abundances — galaxies: halos — galaxies: individual (NGC 4631) — galaxies: starburst

1. Introduction

For understanding the chemical evolution of galaxies and clusters of galaxies, precise knowledge about metal production from type Ia (SN Ia) and type II (SN II) supernovae (SNe) is of vital importance. X-ray imaging spectroscopy of supernova remnants (SNRs), galaxies, and intra-cluster medium (ICM) has shown that metal abundances generally vary from source to source. However, Sato et al. (2007a) determined the abundances of O, Ne, Mg, Si, and Fe in several galaxy clusters based on Suzaku observations, and found that the abundance patterns are commonly represented by a combination of type Ia and type II supernova products with an occurrence number ratio of 1:3.5, based on theoretical yields from SN II and SN Ia. In order to further look into the past history of the two types of supernova, we need more precise knowledge about the metal yields from the different SNe types. It is, however, quite difficult to extract pure supernova products, particularly for the X-ray emitting hot gas. When we observe young supernova remnants, there is always a mixture of supernova ejecta and surrounding ISM; the line intensities also strongly depend on the ionization condition. One way to provide a good constraint is to observe X-ray halos around starburst galaxies, which are considered to be maintained by the enhanced SNe II activity in recent time.

Recent X-ray observations of star-forming galaxies showed that metals are contained in the extended hot halo of the galaxies. For M 82 and NGC 253, RGS (reflection grating spectrometer) spectra for several sliced regions along the outflow axis showed lines from highly ionized O, Ne, Mg, Si, and Fe (Read & Stevens 2002; Bauer et al. 2007). The observed intensity ratios of the lines indicate that the gas is cooling as it travels outward from the galaxy disk, and that the gas around NGC 253 could partly be out of ionization equilibrium. Suzaku observations of a “cap” region of M 82, which is 11.6 kpc north of the galaxy and is possibly a termination region of the hot-gas outflow, showed a spectrum consisting of emission lines from O through Fe (Tsuru et al. 2007). These spectral features strongly suggest that fresh metal-rich gas produced in the star-forming region is flowing out mainly along the minor axis of galaxies. However, the metal abundances in the halo gas have so far not been well-constrained. RGS data are limited in statistics, and both the EPIC and the ACIS instruments do not have sufficient energy resolution below 1 keV (e.g., Tüllmann et al. 2006). Suzaku offers a good opportunity to measure the metallicity of the outflowing hot gas.

NGC 4631 is a nearby Sc/SBd galaxy with an edge-on morphology, with the distance estimated to be about 7.5 Mpc, where 1’ corresponds to 2.2 kpc. The estimated mass by the Tully–Fisher relation is $2.6 \times 10^{10} M_\odot$ (Strickland et al. 2004). The inclination and position angle are 81° and 356°, respectively. This galaxy is suitable for Suzaku observations of the X-ray halo maintained by its SN activity. With its radio halo (Hummel & Dettmar 1990) and warm IR ratio, it is classified as being a mild disk-wide starburst galaxy (Golla & Wielebinski 1994). An extended X-ray halo was discovered by ROSAT (Wang et al. 1995), and it has been well studied with Chandra (Wang et al. 2001; Oshima 2003; Strickland et al. 2004) and XMM-Newton (Tüllmann et al. 2006). The size of the halo is several arcminutes, and no X-ray counterpart for the central AGN has been detected (Strickland et al. 2004). The association of an Hα filament with the X-ray emission has been discovered (Wang et al. 2001), and FUSE also detected O vi lines from a region at 2’ above the disk (Otte et al. 2003). These results strongly suggest that a halo around NGC 4631 is the site of galactic outflow or a fountain, where the gas is floating up from the disk due to the SN energy input, and possibly cooling.

Another important feature of the halo is extended synchrotron radio emission, which is observed from several star-forming galaxies (e.g., Veilleux et al. 2005). These radio
Fig. 1. Left: The X-ray image of NGC 4631 observed with Suzaku in the 0.6–0.7 keV energy band. Right: The X-ray contour map in linear scale from 0.5–2.0 keV overlaid on an optical image taken by DSS. For both images, the observed XIS 0, 1, 3 images were added on the sky coordinates after removing each calibration source region, and smoothed with $\sigma = 16$ pixel or $\sim 17''$ Gaussian profile. Estimated components of extragalactic X-ray background (CXB) and instrumental background (NXB) were subtracted, and the exposure was corrected, though vignetting was not corrected. The region where energy spectra were extracted are shown by solid and dotted lines in the right figure, for the halo and disk regions, respectively. Two vertical lines show the region where we took the surface brightness profiles in subsection 3.2.

Table 1. Suzaku observation logs for NGC 4631.

<table>
<thead>
<tr>
<th>Object</th>
<th>Sequence No.</th>
<th>Observation date</th>
<th>Pointing* (RA, Dec) J2000.0</th>
<th>Exposure ks</th>
<th>After screening (BI/FI) ks</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 4631</td>
<td>801019010</td>
<td>2006-11-28 03:23–2006-11-29 21:55</td>
<td>(12h42m09s3, +32°32'52&quot;)</td>
<td>81.1</td>
<td>75.9/76.1</td>
</tr>
</tbody>
</table>

* Average pointing direction of the XIS, written in the RA$_\text{NOM}$ and DEC$_\text{NOM}$ keywords of the event FITS files.

Halos are populated with relativistic electrons together with magnetic fields on an order of $10^3$ G. The radial orientation of the magnetic field lines suggests that the field has been carried into the halo region by the outflow of hot gas (Golla & Hummel 1994). In some cases, the hot gas may be confined in the halo when the magnetic pressure exceeds the thermal pressure (Wang et al. 1995). To constrain how the non-thermal energy is distributed in the halo, it is important to look into the possibility of non-thermal emission in the hard X-ray band.

Throughout this paper we adopt a Galactic hydrogen column density of $N_H = 1.27 \times 10^{20}$ cm$^{-2}$ (Dickey & Lockman 1990) in the direction of NGC 4631. The solar abundance table is given by Anders and Grevesse (1989), and the errors are the 90% confidence limits for a single interesting parameter.

2. Observation and Data Reduction

2.1. Observation

Suzaku carried out observations of the starburst galaxy NGC 4631 in 2006 November (PI: N. Y. Yamasaki) with an exposure of 81 ks. The observation log is given in table 1. The X-ray Imaging Spectrometer (XIS: Koyama et al. 2007) instrument consists of a back-illuminated (BI: XIS 1) CCD sensor and two front-illuminated (FI: XIS 0, 3) sensors. The XIS was operated in the Normal clocking mode (8 s exposure per frame), with the standard 5 × 5 or 3 × 3 editing mode. The observed X-ray image in the 0.6–0.7 keV band and the XIS contour image in the 0.5–2.0 keV range overlaid on the optical image by DSS are shown in figure 1.

2.2. Data Reduction

We used version 2.0.6 processing data (Mitsuda et al. 2007), and the analysis was performed with HEAsoft version 6.4 and XSPEC 11.3.2aj. In the analysis of XIS data, we selected ELEVATION $> 15^\circ$ of the data set to remove stray-light from the day Earth limb; also, the light curve of each sensor in the 0.3–10 keV range with a 16 s time bin was also examined so as to exclude periods of an anomalous event rate greater or less than $\pm 3 \sigma$ around the mean. After the above screenings, the remaining exposures of the observations decreased by $\sim 7\%$, as shown in table 1. Event screening with cut-off rigidity (COR) was not performed using our data.

In order to subtract the non–X-ray background (NXB), we used a dark-Earth database, provided by the “xisnxbgen” tools task (Tawa et al. 2008). Although it is known that the optical blocking filters of the XIS have gradually been contaminated...
by outgassing from the satellite, we included these effects in a calculation of the Ancillary Response File (ARF) by the “xisimarfgen” ftools task (Ishisaki et al. 2007). We then generated two different ARFs for the spectrum of each region, A\textsuperscript{U} and A\textsuperscript{B}, which respectively assumed uniform sky emission and the observed XIS image. The task wrote a value, “SOURCE_REG_RATIO”, which represents the flux ratio in the assumed spatial distribution on the sky inside the spectral accumulation region to the entire model, in the ARF file header to evaluate the flux within the region. Since the energy resolution has slowly degraded after the launch, due to radiation damage, this effect was included in the Redistribution Matrix File (RMF) by the “xisrmfgen” ftools task.

We reprocessed the HXD data with the CALDB files of 2008-04-01 version, and applied data reduction by standard criteria. The HXD data was cleaned by the Earth elevation angle > 5°, the cut-off rigidity > 6 GV, and was also processed by applying a dead-time correction. After the screening, the exposure time of the HXD data was 73.3 ks. We used the ae\_hxds\_pinflate\_3\_20070914.rsp file and ae801019010hxd\_pinxnome\_3\_20070914.rsp file as the response and the non-X-ray background (NXB) files, respectively; we also simulated the 100Ms accumulation of the cosmic X-ray background data, as described in NASA web site\textsuperscript{1} using ae\_hxds\_pinflate3\_20070914.rsp as a response file.

3. Analysis and Results

3.1. XIS Spectra and the Galactic Background

We extracted spectra for three regions from the optical and X-ray images, as shown in figure 1:

1. Disk component: a rectangular region of 12\arcmin \times 3\arcmin and \( r < 6\arcmin \) circle centered on (RA, Dec) = (1\textsuperscript{14}2\textsuperscript{m}08\textsuperscript{s}, +32\textsuperscript{\circ}32\textsuperscript{\arcmin}29\textsuperscript{\arcsec}) (35.5 arcmin\textsuperscript{2}).

2. Halo component: a circular region of \( r < 6\arcmin \) from the same center position of the disk component and outside the disk region (77.6 arcmin\textsuperscript{2}).

3. Background: outside of the above-mentioned disk and halo region (\( r > 6\arcmin \)).

We first fitted the spectra of the background region and produced the extra-galactic cosmic X-ray background (CXB) and Galactic emission. This was because the O\textsuperscript{VII} and O\textsuperscript{VIII} lines from the Galactic emission affected these lines from NGC 4631 (see also Sato et al. 2007a). We assumed either a one or two temperature apec model for the Galactic emission (Lumb et al. 2002), and tested the following two models: apec + phabs \times power-law, and apec\textsubscript{1} + phabs \times (apec\textsubscript{2} + power-law), where the apec models had a fixed metal abundance at 1 solar with zero redshift, and the absorption column for “phabs” was fixed to the Galactic value. The 0.4–5.0 keV spectra for the BI and FI sensors for all regions were fitted simultaneously, excluding an energy range of anomalous response around the Si K-edge (1.825–1.840 keV). The results of those fits are given in table 2. In both cases, the surface brightness of the CXB component is consistent with the averaged value of \( \sim 10 \) photons cm\textsuperscript{-2} s\textsuperscript{-1} sr\textsuperscript{-1} keV\textsuperscript{-1} at 1 keV (Gendreau et al. 1995) with fluctuations for this sky area. Afterwards, we adopted the two-temperature model based on an F-test of these results. The intensity of the O\textsuperscript{VII} line is \( 4.4 \pm 0.8 \) photons cm\textsuperscript{-2} s\textsuperscript{-1} sr\textsuperscript{-1} (this unit is hereafter refereed to as the Line Unit or LU), which is almost the same as, or slightly smaller than, the previously reported values (see e.g., Sato et al. 2007b; McCammon et al. 2002). If we subtract the energy spectrum of the background from those of the halo and disk regions, the resultant line intensities without correcting the absorption effect are \( \sim 17.5 \pm 4.1 \) LU for O\textsuperscript{VII} and \( \sim 12.0 \pm 3.9 \) LU for O\textsuperscript{VIII} in the halo and \( \sim 5.1 \pm 1.6 \) LU for O\textsuperscript{VII} and \( \sim 5.8 \pm 0.8 \) LU for O\textsuperscript{VIII} in the disk region.

In order to take into account both the existence of the Galactic component, itself, and propagation of its statistical error, we simultaneously fitted all (background, halo, disk) regions with the same model: phabs \times zphabs \times (vapec\textsubscript{1}+\text{2T} + zbremss + power-law) + constant \times (apec\textsubscript{1} + phabs \times apec\textsubscript{2}). In the model, phabs corresponds to our

<table>
<thead>
<tr>
<th>Parameters</th>
<th>apec\textsubscript{1} + phabs \times power-law</th>
<th>apec\textsubscript{1} + phabs \times (apec\textsubscript{2} + power-law)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( kT_1 ) (keV)</td>
<td>0.145\textsuperscript{+0.008}_{-0.010}</td>
<td>0.114\textsuperscript{+0.010}_{-0.013}</td>
</tr>
<tr>
<td>( \text{Norm}_1 )</td>
<td>0.80 \pm 0.13</td>
<td>1.02 \pm 0.42</td>
</tr>
<tr>
<td>( kT_2 ) (keV)</td>
<td>—</td>
<td>0.310\textsuperscript{+0.096}_{-0.061}</td>
</tr>
<tr>
<td>( \text{Norm}_2 )</td>
<td>—</td>
<td>0.13 \pm 0.13</td>
</tr>
<tr>
<td>( \Gamma )</td>
<td>1.68 \textsuperscript{+0.06}_{-0.06}</td>
<td>1.58 \textsuperscript{+0.07}_{-0.07}</td>
</tr>
<tr>
<td>( \text{Norm}\textsuperscript{4} )</td>
<td>0.93 \pm 0.05</td>
<td>0.85 \pm 0.09</td>
</tr>
<tr>
<td>( \chi^2/\text{dof} )</td>
<td>396/375</td>
<td>382/373</td>
</tr>
</tbody>
</table>

* The apec components for the spectra in the background region of NGC 4631 with one or two temperature models (apec) for Galactic emissions, and a power-law model for CXB.

\textsuperscript{1} Normalization of the apec components divided by the solid angle, \( \Omega\textsuperscript{2} \), assumed in the uniform-sky ARF calculation (20\arcmin radius), \( \text{Norm} = \int n_{\text{H}I} dV / [4\pi(1+z)^2 D\textsubscript{A}^2] / \Omega\textsuperscript{2} \times 10^{20} \text{ cm}^{-3} \text{ arcmin}^{-2} \), where \( D\textsubscript{A} \) is the angular distance to the source.

\textsuperscript{2} Normalization of the power-law component divided by the solid angle same as the normalization of apec, in units of \( 10^{-6} \text{ photons keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2} \) at 1 keV.

\textsuperscript{1} \{http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/pin,cxb.html\}.
Galactic absorption with fixed $N_H = 1.27 \times 10^{20} \, \text{cm}^{-2}$. The term $(\text{apec}_1 + \text{phabs} \times \text{apec}_2)$ represents the Galactic component with a normalization factor to keep a uniform surface brightness. Based on the previous fits, we fixed the temperatures of the Galactic emission, $\text{apec}_1$ and $\text{apec}_2$, to be 0.114 keV and 0.310 keV, respectively, with 1 solar abundance and zero redshift. The power-law component, which represents the CXB, was set to be common for all three regions.

For the ISM emission from NGC 4631, $\text{phabs}$ corresponds to the intrinsic absorption. The hot X-ray halo around NGC 4631 was modeled either with a one or two-temperature collisionally ionized plasma with various metal abundances given by the vapec model. Note that the abundances were common for both temperature components, and we combined the metal abundances into five groups as O, Ne, (Mg and Al), (Si, S, Ar, and Ca), and (Fe and Ni). Because we found that the continuum emission above 2 keV cannot be fitted only with the CXB, we added a $\text{zbremss}$ model of $kT = 10 \, \text{keV}$ for the low-mass X-ray binary (LMXB) component. For the spectrum of the background region, $\text{phabs}$ and the normalizations of $\text{vapec}$ and $\text{zbremss}$ were all fixed to be 0.

The resultant spectra are shown in figure 2, and the parameters are summarized in table 3. For the single-temperature ISM model, the resultant temperatures are $kT = 0.297 \, \text{keV}$ for the disk and 0.290 keV for the halo, respectively. The emission-line profiles for Si and S are difficult to distinguish, and the abundance value is almost consistent with 0. The fit statistics shown in table 3 support the two-temperature model. The two-temperature model gives a larger absorption column and a larger intrinsic luminosity than the single-temperature model. The power-law index of the CXB component was obtained to be $1.48^{+0.06}_{-0.03}$, and the intensity of the LMXB component for the disk corresponds to $\sim 3 \times 10^{39} \, \text{erg s}^{-1}$, which is consistent with the $L_X - M$ relation for spiral galaxies (Gilfanov 2004). A fraction of the LMXB component in the halo region is considered to be due to the extended tail of the telescope PSF. We consider that the two-temperature model actually approximates multi-temperature emission, and it is represented by emission-peak temperatures for O VII and O VIII with a lower metal abundance. However, we did not further carry out a detailed multi-temperature analysis, given the statistical quality of the data.

We note possible systematic errors due to the assumption of the contamination model of the XIS. When we change the thickness of the contamination by $\pm 10\%$, the flux and the temperature of the $kT_1$ component of the halo changes about 30%, and 3%, respectively. Thus, the abundances of metals also change by $\sim 10\%$. The $kT_2$ value of the halo and $kT_1$ and $kT_2$ of the disk change only by $1\%$.

We briefly compare with the previous results for NGC 4631 here. Wang et al. (2001) reported higher temperatures ($0.18 \pm 0.02$ and $0.61 \pm 0.1 \, \text{keV}$) and lower ($0.08 \pm 0.04$) metal abundances after subtracting the blank field of the similar foreground absorption. Tüllmann et al. (2006) observed with XMM-Newton and detected halo emission up to 9.1 kpc from the disk. They sliced the halo into 8 regions, and fitted the spectra with the 2-temperature Raymond–Smith plasma model with the cosmic metal abundance. The resultant temperatures are $kT_{\text{soft}} \sim 0.17 - 0.07 \, \text{keV}$ and $kT_{\text{hard}} \sim 0.28 - 0.2 \, \text{keV}$. Considering the different plasma code and the assumed metal abundance, the agreement of the results is fairly good.

**Fig. 2.** Panels show the observed spectra after subtracting the NXB component for all regions of NGC 4631, which are denoted in the panels; they are plotted by black and red crosses for BI and FI, respectively. The spectra were not corrected for the integrated area. They were fitted with the model: $\text{phabs} \times (\text{vapec}_{1; T} + \text{zbremss} + \text{power-law}) + \text{constant} \times (\text{apec}_1 + \text{phabs} \times \text{apec}_2)$, as shown by black and red lines for the BI and FI spectra. For simplicity, only the model components for BI spectra are shown. The green and blue lines are the ISM component by $\text{vapec}$, cyan and gray are the Galactic background emission by $\text{apec}_1$ and $\text{apec}_2$, magenta and orange are the LMXB and CXB component, respectively. The lower panels show the fit residuals in units of $\sigma$. 

by guest
on 16 September 2017
Table 3. Summary of the best-fit parameters of one or two power components by simultaneous fits of all regions.

<table>
<thead>
<tr>
<th></th>
<th>ISM 1T</th>
<th>Disk</th>
<th>Halo</th>
<th>ISM 2T</th>
<th>Disk</th>
<th>Halo</th>
</tr>
</thead>
<tbody>
<tr>
<td>$kT_1$ (keV)</td>
<td>$0.297^{+0.009}_{-0.016}$</td>
<td>$0.290^{+0.027}_{-0.053}$</td>
<td>$0.290^{+0.025}_{-0.016}$</td>
<td>$0.098^{+0.005}_{-0.015}$</td>
<td>$0.096^{+0.006}_{-0.015}$</td>
<td></td>
</tr>
<tr>
<td>$Norm_1^*$</td>
<td>4.5</td>
<td>$0.9^{+1.2}_{-0.8}$</td>
<td>8.0</td>
<td>$2.3^{+0.013}_{-0.4}$</td>
<td>4.5</td>
<td>$1.3^{+0.014}_{-0.4}$</td>
</tr>
<tr>
<td>$flux_1$ (erg cm$^{-2}$s$^{-1}$)</td>
<td>$2.2 \times 10^{-13}$</td>
<td>$1.3 \times 10^{-13}$</td>
<td>$1.6 \times 10^{-13}$</td>
<td>$2.3 \times 10^{-14}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$kT_2$ (keV)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$Norm_2^*$</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$flux_2$ (erg cm$^{-2}$s$^{-1}$)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>O (solar)</td>
<td>0.97</td>
<td>$1.34^{+0.016}_{-0.091}$</td>
<td>0.73</td>
<td>$0.69^{+0.012}_{-0.038}$</td>
<td>0.81</td>
<td>$0.55^{+0.012}_{-0.043}$</td>
</tr>
<tr>
<td>Ne (solar)</td>
<td>1.92</td>
<td>$2.18^{+0.54}_{-0.37}$</td>
<td>1.60</td>
<td>$2.11^{+0.012}_{-0.072}$</td>
<td>1.09</td>
<td>$1.14^{+0.012}_{-0.055}$</td>
</tr>
<tr>
<td>Mg, Al (solar)</td>
<td>1.85</td>
<td>$2.29^{+0.46}_{-0.79}$</td>
<td>1.26</td>
<td>$0.70^{+0.012}_{-0.065}$</td>
<td>0.98</td>
<td>$0.14^{+0.012}_{-0.069}$</td>
</tr>
<tr>
<td>Si, S, Ar, Ca (solar)</td>
<td>0.45</td>
<td>$5.98^{+0.20}_{-0.8}$</td>
<td>0.60</td>
<td>$2.65^{+0.012}_{-0.060}$</td>
<td>2.17</td>
<td>$0.83^{+0.012}_{-0.217}$</td>
</tr>
<tr>
<td>Fe, Ni (solar)</td>
<td>1.09</td>
<td>$0.85^{+0.017}_{-0.63}$</td>
<td>0.93</td>
<td>$0.64^{+0.012}_{-0.041}$</td>
<td>0.46</td>
<td>$0.31^{+0.012}_{-0.23}$</td>
</tr>
<tr>
<td>Extra absorption (cm$^{-2}$)</td>
<td>$-4.0^{+4.0}_{-2.0} \times 10^{20}$</td>
<td>$0.0^{+0.0}_{-0.0} \times 10^{20}$</td>
<td>$8.6^{+0.4}_{-0.0} \times 10^{20}$</td>
<td>$6.4^{+0.4}_{-0.0} \times 10^{20}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LMXB flux (erg cm$^{-2}$s$^{-1}$)</td>
<td>$3.0 \times 10^{-13}$</td>
<td>$8.5 \times 10^{-14}$</td>
<td>$2.6 \times 10^{-13}$</td>
<td>$7.8 \times 10^{-14}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot gas luminosity† (erg s$^{-1}$)</td>
<td>$1.9 \times 10^{39}$</td>
<td>$0.9 \times 10^{39}$</td>
<td>$3.1 \times 10^{39}$</td>
<td>$1.6 \times 10^{39}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\chi^2$/dof</td>
<td>1198/1114</td>
<td>1172/1109</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Normalization of the power component scaled with a factor of $source_{ratio,\text{REG}}/area$, which is $Norm = source_{ratio,\text{REG}} \times n_e n_H dV / 4 \pi (1 + z^2) D_L^2 \times 10^{-20}$ cm$^{-2}$ arcmin$^{-2}$, where $D_L$ is the angular distance to the source.
† Flux within the accumulated region between 0.5 and 2 keV.
‡ Intrinsic luminosity between 0.5 and 2 keV.

Fig. 3. Count rate profile of hard (0.85–1.5 keV) and soft (0.4–0.85 keV) X-ray bands without subtracting the background and the hardness ratio in the north (left) and south (right) sides. The region is shown in figure 1. The dashed lines in the count rate profile are drawn to show the averaged rate taken from the background region for the spectral fitting.

3.2. Hardness Ratio

We produced count rate profiles in a rectangular region of 7.5 kpc $\times$ 42 kpc, as shown in figure 1 in two X-ray energy bands, 0.4–0.85 and 0.85–1.5 keV. With Chandra, Strickland et al. (2004) also showed a surface brightness profile in the 0.3–1 keV region along the minor axis, and found that an exponential model was preferred over the Gaussian or power-law models. We fitted the profile with an exponential + constant model, as shown in figure 3, in which the constant component represents the sum of the X-ray and non-X-ray backgrounds. The fit well represents the data, and can not be rejected within a confidence level of 95%. The constant levels are consistent within errors to the same for the north and south sides.

The obtained scale heights are summarized in table 4. These values are larger than those by Strickland et al. (2004), and could be due to the difference of the data region used in the fit. The scale-height values in table 4 are consistent with each other to within 90% errors, but those in the hard band tend to be smaller than those in the soft band for both sides of the disk. This corresponds to a spectral softening, consistent with the feature obtained by a spectral fit with XMM-Newton (Tüllmann et al. 2006).
We calculated the hardness ratio (HR) for the exponential component after subtracting the constant levels with errors; the results are plotted in figure 3. If we assume single-temperature thermal emission for the disk with the abundances shown in table 3, temperatures of \( kT = 0.2, 0.3, \) and \( 0.4 \) keV give HR values of 0.268, 0.610, and 0.809, respectively. Toward the outer region at \( > 10 \) kpc from the disk, \( kT \) is consistent with \( > 0.2 \) keV. The small or no decline of the temperature may imply that the gas is adiabatically expanding into a vacuum with small mechanical work.

### 3.3. Search for the Hard X-Ray Emission

Since NGC 4631 is accompanied by a strong radio halo, which is likely to be due to synchrotron emission by relativistic electrons, one can expect inverse Compton emission in the hard X-ray band. We searched for hard X-ray emission with the PIN detector of the HXD over the 0.2–10 keV energy band. We searched for hard X-ray emission by subtracting the constant levels with errors; the energy spectrum was found to be consistent with the expected CXB level. Due to the current uncertainty of the NXB estimation, we scaled the normalized NXB by \( 3\% \) (Kokubun et al. 2007), and the spectrum was fitted by the phabs + powerlaw model with a fixed photon index of \( \Gamma = 2.0 \) in the 12–60 keV region.

The resultant upper limit corresponding to the 1 \( \sigma \) level of the flux was \( 5.5 \times 10^{-13} \) erg cm\(^{-2}\) s\(^{-1}\) in the 12–60 keV region; the estimated contribution from LMXBs with an energy spectrum of \( kT = 10 \) keV was \( 4 \times 10^{-12} \) erg cm\(^{-2}\) s\(^{-1}\). Very Large Array (VLA) observations at 1.49 GHz indicated a radio halo of NGC 4631 with a brightness of about 1.22 Jy (Hummel & Dettmar 1990). If we assume an inverse Compton process with 2.7 K photons scattered by the same relativistic electrons responsible for the radio halo, the strength of the magnetic field is constrained. Following a prescription given by Harris and Grindlay (1979), we derived the lower limit of the magnetic field strength to be \( B > 0.5 \) \( \mu \)G, which is consistent with the previous estimation of 5 \( \mu \)G from the polarized component of the radio emission (Hummel et al. 1991).

### 4. Discussion

Suzaku observations of NGC 4631 showed significant emission lines from an extended halo region, including those from O, for the first time. We examined an abundance pattern for the X-ray halo in the form of the number ratio to O as shown in figure 4. To make this plot, the \( Z/O \) ratios were determined by two parameter errors from the simultaneous fit of all regions, as described in subsection 3.1. In this plot, the SN Ia yields were taken from the W7 model in Iwamoto et al. (1999). For SN II, Nomoto et al. (2006) gave average yields for the Salpeter’s IMF of stellar masses from 10 to 50 \( M_\odot \) with a progenitor metallicity of \( Z = 0.02 \). If the metallicity of progenitors increases to \( Z = 1 \), the relative abundances of the ejecta increase by at most 20% for Fe/O. Also, the solar-abundance template of Anders and Grevesse (1989), and the average abundance pattern for 4 clusters and groups (Sato et al. 2007a) are plotted together. The pattern in clusters was well-fitted by a combination of SN Ia and SN II with a ratio of 1:3.5. The metal abundance of NGC 4631 halo disagrees with that of SN Ia, and the cluster average, but is consistent with the SN II yields. In the disk component, Fe shows a relatively higher abundance, and the abundance pattern is consistent with the solar abundance given by Anders and Grevesse (1989).

For studying the energetics of the gas, we estimated the density, mass, and total energy of the X-ray emitting gas. As shown in figure 3, the X-ray profile of the halo is very smooth, and there is no boundary recognized between the disk and the halo. Hereafter, we do not discriminate the disk and the halo component, and treat them at the same time. We assume a simple exponential model of \( n(z) = n_0 \exp(-z/h) \), with \( z \) indicating the distance from the galactic plane, within a radius of 10 kpc for the coronal gas. Since the scale height of the surface brightness is about 3.5 kpc, as shown in table 4, we can adopt the density scale height to be \( h = 7 \) kpc. A single-temperature model gave us a lower limit of the density at the disk as \( n_0 = 2 \times 10^{-3} \) cm\(^{-3}\), and the pressure as \( n_0 T = 7 \times 10^{5} \) cm\(^{-3}\) K, which are consistent with the previous values by Wang et al. (1995, 2001). With this density, the total mass of the X-ray emitting gas is \( 1.3 \times 10^{6} \) \( M_\odot \), and the stored thermal energy is \( 2 \times 10^{56} \) erg. Assuming an O abundance of 0.8 solar, the O mass in the hot gas in both the disk and the halo is \( \sim 10^{-6} \) \( M_\odot \).

Since the cooling time in the disk is about \( \sim 6 \times 10^8 \) yr, assuming the cooling function of Sutherland and Dopita (1993), the required energy input rate is \( 3 \times 10^{37} \) erg yr\(^{-1}\) and the mass-transfer rate is \( \sim 0.2 \) \( M_\odot \) yr\(^{-1}\), respectively. If one employs a flow time to a radius of 10 kpc, it is about \( 5 \times 10^7 \) yr, and 10-times higher rates for energy input and mass transfer are implied. Wang et al. (1995) estimated the maximum mass flow rate from the density multiplied by the sound velocity to be \( 1.4 \) \( M_\odot \) yr\(^{-1}\). Based on a UV observation of the O VI line, Otte et al. (2003) estimated the flow rate to be 0.48–2.8 \( M_\odot \) yr\(^{-1}\), assuming a cooling flow model by Edgar and Chevalier (1986). Considering the differences in the assumed physical process and condition, the mass-flow rates are in good agreement around an approximate value of \( 1 \) \( M_\odot \) yr\(^{-1}\).

The most likely source of the energy and material in the coronal gas is SNe. The SFR is estimated by the FIR luminosity to be \( 3 \) \( M_\odot \) yr\(^{-1}\) (Strickland et al. 2004). Since NGC 4631 has an edge-on morphology, the emission could be underestimated due to absorption through the disk. Persic et al. (2004) proposed another method to estimate the SFR using the X-ray luminosity of high-mass X-ray binaries (HMXB) in the 2–10 keV band. A typical luminosity ratio of HMXB/LMXB of 0.2 gives a SFR of \( 1.2 \) \( M_\odot \) yr\(^{-1}\). If we assume that all of the flux above 2 keV comes from HMXBs, it gives an upper limit of \( 6 \) \( M_\odot \) yr\(^{-1}\). We note that a spectral fit with a power-law
component with $\Gamma = 1.2$, as suggested by Persic et al. (2004), requires a steep $\Gamma = 1.55$ CXB component. Two independent estimates give a consistent SFR of $\sim 3 M_\odot$ yr$^{-1}$, which is almost the same as, or a little less than, the level in our Galaxy, i.e. $\sim 5 M_\odot$ yr$^{-1}$ (Zinnecker & Yorke 2007). Assuming the Salpeter’s IMF integrated over 0.1 to 50 $M_\odot$, a SFR of 3 $M_\odot$ yr$^{-1}$ gives a SN II rate of $7 \times 10^{-3}$ SN yr$^{-1}$. In addition to SN II, SN Ia of $2.5 \times 10^{-3}$ SN yr$^{-1}$ is expected for the total mass of $2.6 \times 10^{10} M_\odot$ and the SFR of 3 $M_\odot$ yr$^{-1}$ (Sullivan et al. 2006).

If SNe are the source of the energy and the mass of the halo gas estimated above, one SN needs to supply an energy of $3 \times 10^{49} \text{erg}$ and a mass of $\sim 20 M_\odot$, including an O mass of 0.2 $M_\odot$. Therefore, 3% of the typical explosion energy of $10^{51} \text{erg}$ and 20 $M_\odot$ from the ejecta and ambient material must escape into the halo. These values indicate that the halo gas is produced very efficiently. Since one SN produces 0.14 and 1.8 $M_\odot$ of O for SN Ia and SN II, respectively (Iwamoto et al. 1999), a supply of 0.2 $M_\odot$ of O seems to be plausible. The abundance pattern in the halo is, however, well represented by the SN II products, although the above-estimated rate between SN Ia and SN II is $\sim 1:3$. It may imply a selective escape of SN II ejecta into the halo gas, which can result if the occurrence of SN II is concentrated in the star-forming region. In this case, superbubbles are formed and metal-rich hot gas escapes along a chimney to the halo space (Norman & Ikeuchi 1989).

We must note two possibilities that may bias the abundance and temperature estimate. Lallement (2004) pointed out the possible contribution of charge exchange (CX) processes between the galactic wind and gas clouds in the halo. The CX spectrum is dominated by emission lines, and it tends to decrease the apparent temperature of the halo, $kT_1$ in table 3.

The process was seriously evaluated for the M 82 halo (Ranalli et al. 2008) and the M 82 “cap” region (Tsuru et al. 2007), and they found that almost all of the O VII triplet could be produced by CX. In the case of NGC 4631, a dust arch with a mass of a few-times $10^8 M_\odot$ was discovered in the halo, but there seemed to be no connection between the X-ray emission and the dust arch (Taylor & Wang 2003). Thus, the contribution from CX might not be very large, considering the low velocity of the outflow and the low density of the neutral material, which is also suggested by a slow decline of the X-ray temperature. We must wait for improved spectroscopic observations to distinguish the physical process of the emission.

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**Fig. 4.** Number ratios of Ne, Mg, Si, S, and Fe to O for disk and halo regions. Solid, dotted, dashed, and dot-dashed lines correspond to the number ratios of metals to O for the abundance patterns of SNe II yield of Nomoto et al. (2006), solar abundance by Anders and Grevesse (1989), cluster average in Sato et al. (2007a), and SNe Ia yield of Iwamoto et al. (1999), respectively.
Another possibility is the role of dust. Dust of silicates ($\text{Mg}_2\text{SiO}_4$) and other forms with a mass of $\sim 5 M_\odot$ SN$^{-1}$ can be formed 300–600 days after SN II explosions (Todini & Ferrara 2001). Since it requires more than $10^7$ yr to evaporate in a low-density environment with $n = 10^{-3}$ cm$^{-3}$ (Tielens et al. 1994), a significant amount of metals may be held in dust. We hope that future high-resolution X-ray spectroscopy will be able to show the ionization condition of plasmas in the galactic winds more precisely.

5. Conclusion

We determined the temperature and metal abundance of the X-ray emitting halo gas around NGC 4631. The total energy, mass, and metals in the halo can be supplied by SNe with the currently estimated SFR, if the outflow efficiently carries metal-rich gas from the star-forming regions into the halo. The effect of neutral material and dust should be taken into account to understand the plasma properties in the halo.

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