Abundance Patterns in the Interstellar Medium of the S0 Galaxy NGC 1316 (Fornax A) Revealed with Suzaku

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(Received ; accepted )

Abstract

The Suzaku X-ray satellite observed the nearby S0 galaxy NGC 1316, a merger remnant aged 3 Gyr. The total good exposure time was 48.7 ksec. The spectra were well represented by a two-temperature thermal model for the interstellar medium (ISM) plus a power-law model. The cool and hot temperatures of the thermal model were 0.48±0.03 and 0.92±0.04 keV, respectively. The excellent spectral sensitivity of Suzaku enables for the first time to measure the metal abundances of O, Ne, Mg, Si, and Fe in the ISM. The resultant abundance pattern of O, Ne, Mg, Si, and Fe is close to that of the new solar abundance determined by Lodders (2003). The measured abundance pattern is compared with those of elliptical galaxies and an S0 galaxy, observed with Suzaku. Considering the metal-enrichment from present Type Ia supernovae, the near-solar abundance pattern of the ISM in NGC 1316 indicates an enhanced α/Fe ratio of stellar materials in the entire galaxy, like in giant elliptical galaxies.

Key words: galaxies: individual (NGC 1316), galaxies: interstellar medium, galaxies: abundances

1. Introduction

Hot X-ray emitting interstellar medium (ISM) carries important information about the history of star formation and evolution of galaxies. The metals in the ISM in early-type galaxies have been enriched by type Ia supernovae (SNe Ia) and stellar mass loss. Since SNe Ia do not produce O or Mg, abundances of these elements in the ISM reflect stellar abundances. Thus, the abundance pattern of the ISM can play a key role in studying the origin of metals.

The ASCA satellite first enabled us to measure the metal abundances in the ISM of the early-type galaxies (e.g., Awaki et al. 1994; Loewenstein et al. 1994; Mushotzky et al. 1994; Matsushita et al. 1994). These galaxies have about 1 solar iron abundance, employing a multi-temperature plasma model (Buote & Fabian 1998), or considering uncertainties in the Fe-L atomic data (Arimoto et al. 1997; Matsushita et al. 1997; Matsushita et al. 2000). Chandra and XMM-Newton measured the metal abundances and spatial distributions of metals in the ISM of the early-type galaxies, because of their large effective area and good angular resolution (Humphrey et al. 2004; Humphrey & Buote 2006; Werner et al. 2006; Tozuka & Fukazawa 2008). In particular NGC 5044, NGC 1399, and NGC 4636, the abundances of non-Fe elements have good constraints with Chandra and XMM (Buote et al. 2003; Ji et al. 2009). The observed abundance patterns are consistent with the solar ratio. However, O and Mg abundances of relative faint X-ray galaxies still remain highly uncertain, due to a highly asymmetric energy response in the low-energy region below 1 keV and a strong instrumental Al line of these missions, respectively. The Suzaku XIS (Koyama et al. 2007) has an improved line spread function due to a very small low-pulse-height tail below 1 keV, with a lower and more stable background level compared to the Chandra ACIS and the XMM-Newton EPIC. The abundance patterns in the ISM of several giant elliptical galaxies, including NGC 1399 and NGC 1404 (Matsushita et al. 2007), NGC 720 (Tawara et al. 2008), and NGC 4636 (Hayashi et al. 2009), have been revealed by recent Suzaku observations. The derived Fe abundances of the ISM are about 1 solar, and the abundance patterns are close to that of the new solar abundance determined by Lodders (2003). From these results, the contribution of SNe Ia and stellar mass loss to the metal enrichment of the ISM and intracluster medium were discussed. However, NGC 4382 is the only S0 galaxy whose ISM abundance pattern has so far been derived with Suzaku (Nagino & Matsushita 2010). The O/Fe ratio of the ISM in this galaxy is smaller by a factor of two as compared to those in the four elliptical galaxies.

In terms of the cosmology dominated by cold dark matter, it is considered that at least some elliptical galaxies were formed by a hierarchical formation scenario, in which larger spheroidals were assembled relatively late through mergers of the late-type galaxies of comparable
mass (De Lucia et al. 2006 and references therein). In contrast, S0 galaxies in clusters of galaxies are considered to be formed through morphological transformations, from infalling gas-rich spiral galaxies to gas-poor S0 galaxies. This is because spiral galaxies were much more common, and S0 galaxies were much rarer, in distant than nearby galaxy clusters (e.g., Poggianti et al. 2009; Desai et al. 2007; Smith et al. 2005; Postman et al. 2005). In spite of these differences, the elliptical and S0 galaxies have been treated together in most of the past studies. However, since there are possible differences in the formation scenario, we need to study the elliptical and S0 galaxies separately.

The abundance pattern of stars reflects their formation history, since a longer formation time provides a higher concentration of trapped SNe Ia products to the stars. If the elliptical and S0 galaxies have different formation histories, their stellar metallicity and/or present SN Ia rate may be different. The stellar metallicity of the early-type galaxies has often been investigated in optical observations of their central regions (e.g., Thomas et al. 2005; Bedregal et al. 2008; Walcher et al. 2009). However, there may be systematic uncertainties in the assumption of the age-population of stars, and in atomic physics. Also the values of solar abundances have changed enormously, considering the three-dimensional hydrostatic atmosphere and non-local thermodynamic equilibrium (Asplund 2005). In contrast, X-ray observations of the ISM, show much simpler atomic data and temperature structures as compared to those in the optical spectra, and we can observe the entire region of each galaxy, although the metals in the ISM are a mixture of those from stars and recent SNe Ia. Considering these, further X-ray studies of S0 galaxies are thought to be important.

NGC 1316 is a peculiar S0 galaxy, with numerous tidal tails. This galaxy has a surprisingly high central surface brightness, and a lower velocity dispersion ($\sigma = 227^{+33}_{-33}$ km s$^{-1}$; Goudfrooij et al. 2001) for its galaxy luminosity than other elliptical galaxies with similar luminosities (e.g., Schweizer 1980; Schweizer 1981; D’Onofrio et al. 1997). Due to these features, NGC 1316 has been thought to have undergone a major merger relatively recently. The merger age is estimated to be $\sim$3 Gyr, based on the age of the bright globular clusters (Goudfrooij et al. 2001). Therefore, NGC 1316 is good target for investigation of the galaxy formation process through mergers. Measurements of the absorption-line indices of the central region, or $1/10 r_e$ of NGC 1316, indicates a small over-abundance of $\alpha$/Fe ratio of $[\alpha/Fe]=0.15$ (Thomas et al. 2005), which is smaller than the $[\alpha/Fe]=-0.3$, in center of the giant elliptical galaxies (e.g. Thomas et al. 2005; Pipino et al. 2009). Here, $r_e$ is the effective radius of the galaxy. These line indices also indicate a somewhat younger age of 3–5 Gyr (Bedregal et al. 2008).

ROSAT observations of NGC 1316 detected a thermal emission component from hot ISM (Kim et al. 1998), using Chandra data of an good exposure of 25 ksec, Kim & Fabbiano (2003) found that the ISM has a temperature in the 0.5–0.6 keV range and a 0.3–8 keV luminosity of $3.1\times10^{40} \text{ erg s}^{-1}$. The metal abundance of the ISM were reported to be 0.2–1.3 solar adopting the solar abundance table by Anders & Grevesse (1989). NGC 1316 hosts radio lobes, that generate inverse-Compton X-rays as well as synchrotron radio emission (e.g. Feigelson et al. 1995; Kaneda et al. 1995; Isobe et al. 2006). Although this means that NGC 1316 harbors an active galactic nucleus (AGN), Iyomoto et al. (1998) and Kim & Fabbiano (2003) showed that the present activity of the AGN is very low. A recent Suzuki observation detected the inverse-Compton X-ray up to 20 keV utilizing Suzuki from the west lobe (Tashiro et al. 2009).

In this paper, we analyze Suzuki XIS data of NGC 1316. We use a distance of 18.6 Mpc to NGC 1316 based on the Hubble Space Telescope measurements of Cepheid variables (Madore et al. 1999), and a redshift of 0.005871 including proper motion (Longhetti et al. 1998). We use the new solar abundances in Lodders (2003).

### 2. Observation and Data Reduction

Suzaku observed NGC 1316 in 2006 December, using the XIS (Koyama et al. 2007). The XIS consists of two front-illuminated (FI: XIS0 and XIS3) CCD cam-
The apec components for spectra in the background region of NGC 1316 with the ICM component of the Fornax cluster, absorbed or non-absorbed MWH component, LHB component for the Galactic emission, and a power-law model for CXB.

Table 1. Best-fit parameters for the apec components + power-law models.*

| Parameters               | (i)          | (ii)         |
|--------------------------|--------------|--------------|
| $N_{\text{OTHERS}}$     | 1.6 (fix)    | 1.6 (fix)    |
| $N_{\text{ICM}}$‡       | 1.92×10^{20} (fix) | 1.92×10^{20} (fix) |
| $kT_{\text{ICM}}$       | 0.74±0.06    | 0.74±0.06    |
| Abundance (solar)        | 0.3 (fix)    | 0.3 (fix)    |
| $N_{\text{MWH}}$‡       | 1.88±0.36    | 1.91±0.35    |
| $kT_{\text{MWH}}$       | 0.30±0.04    | 0.30±0.04    |
| Abundance (solar)        | 1 (fix)      | 1 (fix)      |
| $N_{\text{LHB}}$‡       | 2.79±0.59    | 2.73±0.60    |
| $\chi^2$/d.o.f.         | 490/359      | 490/359      |

* The apec components for spectra in the background region of NGC 1316 with the ICM component of the Fornax cluster, absorbed or non-absorbed MWH component, LHB component for the Galactic emission, and a power-law model for CXB.
† Normalization of the power-law component divided by the solid angle same as the normalization of apec, assuming thresholds on the Earth elevation angle of $20^\circ$ radius, in units of $10^{-3}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ arcmin$^{-2}$ at 1 keV.
‡ Normalization of the apec components divided by the solid angle same as the normalization of apec, $\text{Norm} = \int n_e n_H dV / (4\pi (1 + z)^2 D_A^2) / \Omega_0 \times 10^{-17}$ cm$^{-5}$ arcmin$^{-2}$, where $D_A$ is the angular distance to the source.

3. Analysis and Results

3.1. Extraction Regions of Spectra

The observed X-ray image in the 0.4–5 keV range is shown in figure 1, superposed on an optical contours from the Digitized Sky Survey. We used the following two regions to extract spectra: one is NGC 1316 region, which is a circular region with a 5$''$ radius shown in a green circle in figure 1. The other is background region, which is the entire XIS field of view excluding the NGC 1316 region. We excluded the region around NGC 1317, shown in a red circle in figure 1. In addition, three calibration sources, with emission peaks at 5.9 keV, are located at the corners of the XIS. We included these regions to improve the photon statistics because the ISM emits almost no photons above 5 keV.

3.2. Estimation of Background Spectra

In order to estimate the background components, we first fitted the spectra extracted over the background region. Since the NXB component was already subtracted, the remaining background consisted of extra-galactic cosmic X-ray background (CXB), and emission from our Galaxy. We assumed a power-law model for the CXB component, and a two temperature model from the Galactic emission. Empirically, one thermal component represents the sum of solar wind charge exchange (SWCX) and local hot bubble (LHB), while Milky Way halo (MWH) emits the other thermal component (Yoshino et al. 2009). We also added a thin thermal plasma emission from intracluster medium (ICM) of the Fornax cluster (Tashiro et al. 2009). We thus, fitted the spectra with the following model: phabs × (power-law + apec$_{\text{ICM}}$ + apec$_{\text{MWH}}$)
Fig. 2. NXB-subtracted XIS0 (black) and XIS1 (red) spectra of NGC 1316 (left column), and those of the background region (right column), shown without removing the instrumental responses. The top two and bottom two panels employ the one- and two-temperature model for the ISM, respectively. Black and red lines show the best-fit model for the XIS0 and XIS1, respectively. For simplicity, only the model components for XIS1 spectra are shown. Orange and purple lines are the ISM components, cyan is emission from the ICM of Fornax cluster by apec_{ICM}, magenta and yellow are the Galactic background emission by apec_{MWH} and apec_{LHB}, while blue and green are the CXB and (LMXB + radio lobe) components, respectively. The background components, except power-law_{OTHERS}, are common between the on-source and background spectra, but scaled to the respective data accumulation area.
Table 2. Summary of the best-fit parameters for the NGC 1316 and the background region with 1T for ISM model, 2T for ISM model, and 2T for ISM adding 10% systematic error of Fe-L model.

| Parameters                  | 1T for ISM | 2T for ISM | Fe-L |
|-----------------------------|-----------|-----------|------|
| \( kT_{1T} \) (keV)        | 0.62±0.01 | 0.48±0.03 | 0.40±0.08 |
| \( \text{Norm}_{1T} \) *   | 2.10±0.17 | 1.04±0.24 | 0.95±0.16 |
| \( kT_{2T} \) (keV)        | -         | 0.92±0.04 | 0.93±0.05 |
| \( \text{Norm}_{2T} \) *   | -         | 0.80±0.16 | 0.70±0.12 |
| O (solar)                  | 0.71±0.41 | 0.79±0.31 | 0.71±0.50 |
| Ne (solar)                 | 1.31±0.35 | 0.63±0.23 | 0.66±0.48 |
| Mg, Al (solar)             | 0.43±0.22 | 0.55±0.35 | 0.77±0.81 |
| Si, S, Ar, Ca (solar)      | 0.31±0.20 | 0.48±0.38 | 0.64±0.66 |
| Fe, Ni (solar)             | 0.44±0.09 | 0.73±0.15 | 1.01±0.75 |
| O/Fe (solar)               | 1.61±0.43 | 1.08±0.28 | 0.70±0.51 |
| Ne/Fe (solar)              | 3.00±0.57 | 0.86±0.52 | 0.65±0.52 |
| Mg/Fe (solar)              | 0.98±0.23 | 0.75±0.22 | 0.76±0.26 |
| Si/Fe (solar)              | 0.70±0.27 | 0.66±0.23 | 0.63±0.31 |
| \( kT_{1MC} \) (keV)       | 0.77±0.08 | 0.72±0.04 | 0.72±0.04 |
| \( \text{Norm}_{1MC} \) *  | 2.51±0.51 | 2.83±0.36 | 2.84±0.44 |
| \( kT_{2MWH} \) (keV)      | 0.30±0.03 | 0.28±0.02 | 0.28±0.02 |
| \( \text{Norm}_{2MWH} \) * | 1.44±0.27 | 1.26±0.28 | 1.23±0.21 |
| \( kT_{1LHB} \) (keV)      | 0.1 (fix) | 0.1 (fix) | 0.1 (fix) |
| \( \text{Norm}_{LHB} \) *  | 4.52±0.98 | 4.50±1.00 | 4.37±0.98 |
| \( \chi^2/\text{d.o.f.} \) | 970/703   | 921/701   | 859/692 |

* Normalization of the v apex and apec components scaled with a factor of source ratio / area, which is \( \text{Norm} = \frac{\text{source ratio}}{\text{area}} \int n_e n_H dV / [4\pi (1+z)^2 D_A^2] \times 10^{-17} \text{ cm}^{-5} \text{ arcmin}^{-2} \), where \( D_A \) is the angular distance to the source.

+ apec\(_{LHB}\). Here, the “phabs” factor represents the photoelectric-absorption, whose column density was fixed to the Galactic value of 1.92×10\(^{20}\) cm\(^{-2}\) in the direction of NGC 1316. The “apec\(_{ICM}\)” “apec\(_{MWH}\)” and “apec\(_{LHB}\)” terms mean the thermal emission, in terms of APEC plasma model (Smith et al. 2001), from the ICM, MWH, and LHB, respectively. We assumed that the apec\(_{ICM}\) has a metal abundance fixed at 0.3 solar, while apec\(_{MWH}\) and apec\(_{LHB}\) 1.0 solar. The redshift of apec\(_{ICM}\) was also fixed at 0.005871, while apec\(_{MWH}\) and apec\(_{LHB}\) zero. The power-law slope of the CXB emission was fixed at \( \Gamma = 1.4 \) (Kushino et al. 2002). The spectra from the BI and FI CCDs were simultaneously fitted in the 0.4–5.0 and 0.5–5.0 keV range, respectively.

This model well reproduced the spectra, with \( \chi^2/\text{d.o.f.} = 455/360 \). However, the strength of the power-law representing the CXB was about twice as high as that of Kushino et al. (2002). We consider that this is due to contributions by other sources in NGC 1316, such as the radio lobes and integrated low mass X-ray binaries (LMXBs). The index of the power-law component from the radio-lobes is 1.68 (Tashiro et al. 2009). The integrated spectra from discrete sources in the early type galaxies are approximated with a power-law model with an index of 1.6 (e.g., Xu et al. 2005, Randal et al. 2006). Therefore, we added a power-law component, “power-law\(_{OTHERS}\)” with its index fixed at 1.6, and then fitted the spectra with the following model (i): phabs \( \times \) (power-law\(_{CXB}\) + power-law\(_{OTHERS}\) + apec\(_{ICM}\) + apec\(_{MWH}\) + apec\(_{LHB}\)). The index and normalization of power-law\(_{CXB}\) were fixed at the values by Kushino et al. (2002). The results of the fit are summarized in table 1.

We also examined the following model (ii): phabs \( \times \) (power-law\(_{CXB}\) + power-law\(_{OTHERS}\) + apec\(_{ICM}\) + apec\(_{MWH}\) + apec\(_{LHB}\)). The difference of this model from model (i) is whether or not the MWH component is absorbed by the Galactic column (e.g., Yamasaki et al. 2009; Konami et al. 2009). We summarize the results in table 1. There was no significant difference in the derived parameters between model (i) and (ii). Hereafter, we adopted model (i) as the background model for the spectral fitting, unless otherwise stated.

To evaluate the Galactic emission, we also fitted the O\(_{VII}\) and O\(_{VIII}\) lines of the spectra of the background region with Galssians and a power-law model in the 0.5–0.7 keV range. The resultant intensities of the O\(_{VII}\) and O\(_{VIII}\), without correcting for absorption, are 9.2±3.5 and 3.4±0.7 photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) respectively. These values are consistent with the previously reported values from other sky region (McCannon et al. 2002; Sato et al. 2007; Yamasaki et al. 2009; Konami et al. 2009). Thus, the Galactic foreground emission in the present sky direction is considered typical.
3.3. Emission from NGC 1316

We fitted the spectra of the NGC 1316 region with the model: phabs × vapec_{ISM} + background models. In this model, “phabs” represents the Galactic absorption in the direction of NGC 1316, fixed at \( N_H = 1.92 \times 10^{20} \) cm\(^{-2}\).

The ISM emission of NGC 1316, vapec_{ISM}, was represented by one-temperature (1T) or two-temperature (2T) models, employing the vapec code (Smith et al. 2001). The abundances of He, C, and N were fixed to the solar value. We also divided the other metals into five groups as O, Ne, (Mg & Al), (Si, S, Ar, Ca), and (Fe & Ni), based on the metal synthesis mechanism of SNe, and allowed each group to vary. In the 2T modeling, the two vapec components were assumed to share the same elemental abundances. Using this model, we simultaneously fitted the spectra of the NGC 1316 and background regions using the energy ranges of 0.4–5.0 keV for the BI CCD and 0.5–5.0 keV for the FI CCDs. The normalization of power-law_{OTHERS} was not linked between the two regions, because the number of LMXBs may increase toward the galactic center, and the brightness of the radiolobes may be different. All the other background components were constrained to be the same between the two regions. The normalizations of the ISM components in the background region were fixed at 0.

The results of these fits are summarized in figure 2 and table 2. Several emission lines seen around 0.5–0.6 keV, 0.6–0.7 keV, \( \sim 1.3 \) keV, and \( \sim 1.8 \) keV are identified with Kα lines of O\textsc{vii}, O\textsc{viii}, Mg\textsc{x}, and Si\textsc{xiii}, respectively. The emission bump around 0.7–1 keV corresponds to Fe-L complex, as well as to K-lines from Ne\textsc{ix} and Ne\textsc{x}. These fits are not formally acceptable, mainly, because of discrepancies between the FI and BI spectra of the background region above 2 keV. Although this discrepancy might be related to some remaining problems with the NXB subtraction, they are unlikely to affect the ISM modeling. The 1T model results in \( kT = 0.62 \) keV. The fit statistics shown in table 2 clearly favor the
2T model, which gives the two temperatures as 0.48 and 0.92 keV. The abundance of Fe does not depend very much on the temperature structure of the ISM. Adoption of the 2T model shows, the Fe abundance of the ISM as 0.58–1.15 solar. This value is consistent with the ISM metallicity of 0.4–2.1 solar derived from the Chandra observation derived by Kim & Fabbiano (2003). Here, the value was converted using the solar abundance table by Lodders (2003).

In order to examine the abundance ratios rather than their absolute values, we calculated confidence contours between the abundances of metals (O, Ne, Mg, and Si) and of Fe, using the 2T model for the ISM. The results are shown in figure 3 and table 2. The elongated shape of the confidence contours indicates that the relative values are determined more accurately than the absolute values.

Figure 4 shows metal-to-Fe ratios in NGC 1316 using the 1T and 2T models for the ISM, which were derived from the two-parameter confidence contours shown in figure 3. The O/Fe ratio varies from 1.7 with the 1T model to 1.1 with the 2T model in solar units. On the other hand, the Ne/Fe ratio changes considerably, from ~3 solar with the 1T model to ~1 solar with the 2T case. We note that the Ne abundance is not reliably determined due to an overlap with the strong and complex Fe-L line emissions. The 1T and 2T models give similar values for the Mg/Fe and Si/Fe ratios.

3.4. Systematic Uncertainties in the Abundance Ratios

We also tried to fit the same spectra with the three-temperature vapec model for the ISM. The derived temperature of the third component has a large error, and the Fe abundance increased to 1.03$^{+0.53}_{-0.29}$ in solar units. Meanwhile, the derived abundance ratios are consistent with those from the 2T model. To examine the dependence on the power-law OTHERS component, we fitted the spectra and allowed the index to vary freely. Then, the index decreased to 1.20, but the abundances did not change significantly. Systematic uncertainty associated with the contaminants on the XIS optical blocking filter is less than the statistical errors.

The derived ICM component in subsection 3.3 are including both ICM and ISM components. Considering the point spread function of Suzaku X-ray telescope, ~30% of the ICM component in the background region escaped from the ISM emission in the galaxy region (Serlemitsos et al. 2007). In addition, the ISM emission may extend up to the background region. Therefore, we added another temperature component in the background spectra, and fitted the spectra again. We got almost the same values for the ISM component in the galaxy region. This is because the normalization of the ICM component in the galaxy region is only 10% of that of the ISM, as shown in figure 2.

Because the fits were not formally acceptable, we explored using the C-statistic giving less biased values than $\chi^2$ statistic for Poisson-distributed data (Humphrey et al. 2009). The results of C-statistics fitting hardly improved, $\chi^2$/d.o.f. = 939/701, and the parameters and their errors were almost the same. The large $\chi^2$ mostly comes from the systematic errors of XIS. For examples, because the response matrix of XISs around the Si edge has some problems, the energy range between 1.82 and 1.84 keV was also ignored in the spectral fitting (Koyama et al. 2007). Then, the $\chi^2$/d.o.f improved to 906/691. Furthermore, it is known the discrepancies between the FI and BI spectra of the background region above 2 keV. Ignoring this energy range in the background spectra, the $\chi^2$/d.o.f. become 666/578, and the parameters were almost the same within a few %. The large $\chi^2$ are almost due to systematic uncertainties in the background and calibrations of XIS.

We also investigated the systematic uncertainties in the atomic physics of the Fe-L lines as pointed out in Matsushita et al. (2000) and Matsushita et al. (2007). Convolving the response matrix of XIS, the difference in the Fe-L lines between APEC (Smith et al. 2001) and MEKAL (Mewe et al. 1985) models are typically 10%. Therefore, we fitted spectra in the same way as in section 3.3 but including 10% systematic errors within an energy range of 0.75–1.2 keV. The derived parameters are summarized in table 2, and $\chi^2$/d.o.f became 859/692. The error range in absolute value of each element increased, and the derived Fe abundance became 0.7–1.8 solar. However, increases in the error ranges of the abundance ratios were smaller. Furthermore, ignoring an energy range of 1.82–1.84 keV, and above 2 keV in the background spectra, the $\chi^2$/d.o.f became 605/569.

4. Discussion

We successfully measured the abundance patterns of O, Ne, Mg, Si, and Fe in the ISM of the S0 galaxy NGC 1316 with Suzaku. Figure 4 summarizes the results. We used the new solar abundance table by Lodders (2003). Adopting the result of the 2T model fit, the abundance pattern in the ISM in NGC 1316 is shown to be close to that of the new solar abundance. The abundance patterns of the SN II and SN Ia yields are also plotted in figure 4. Here, the SN II yields by Nomoto et al. (2006) refer to an average over the Salpeter initial mass function of stellar masses from 10 to 50 $M_\odot$, with a progenitor metallicity of $Z = 0.02$. The SNe Ia yields were taken from the W7 model Iwamoto et al. (1999). The abundance pattern in the ISM of NGC 1316 lies between those of SN II and SN Ia, and is consistent with their mixing. Assuming that the O/Fe ratio of the SN II yield is 3.5 solar (Nomoto et al. 2006), then ~70% of Fe in the ISM is synthesized by SNe Ia, and originates from present SNe Ia and from those trapped in stars. Since the 2T and 3T models give the Fe abundance of the ISM of 0.6–1.6 solar, the Fe abundance from SNe Ia would be 0.4–1.1 solar.

The Fe abundance synthesized by present SNe Ia in an early-type galaxy is proportional to $M_{SN}^*\theta_{SN}/\alpha_*$ (see Matsushita et al. 2003 and Nagino & Matsushita 2010 for details). Here, $M_{Fe}^{SN}$ is the Fe mass synthesized in one SN Ia, $\theta_{SN}$ is the SN Ia rate, and $\alpha_*$ is the stellar mass loss rate. Fe in the hot ISM of the galaxy is mainly produced from SNe Ia, since SNe II synthesized far more O
Fig. 4. Abundance ratios of O, Ne, Mg, and Si to Fe for the one-temperature (red) and two-temperature (blue) model of the ISM in NGC 1316. Abundance patterns of NGC 4382 (purple; Nagino & Matsushita 2010), NGC 1332 (orange; Humphrey & Buote 2006), NGC 720 (black crosses; Tawara et al. 2008), NGC 1399 (black closed squares; Matsushita et al. 2007), NGC 1404 (black open squares; Matsushita et al. 2007), NGC 4636 (black stars; Hayashi et al. 2009), and NGC 5044 (black diamond; Buote et al. 2003 and Komiyama et al. 2009) are also shown. Solid and dot-dashed lines represent the number ratios of metals to Fe for the SN II and SN Ia products (Iwamoto et al. 1999; Nomoto et al. 2006).

and Mg than Fe. We used the mass-loss rate from Ciotti et al. (1991) and assumed the age to be 13 Gyr, which is approximated by $1.5 \times 10^{-11} L_B t_15^{-1.3} \dot{M}_\odot \text{yr}^{-1}$, where $t_15$ is the age in units of 15 Gyr and $L_B$ is the B-band luminosity. $M_{Fe}$ produced by one SN Ia explosion is likely to be $\sim 0.6 \dot{M}_\odot$ (Iwamoto et al. 1999). Adopting 0.1–0.5 SN Ia/100 yr/10$^{10}$ $L_B$ as the optically observed SN Ia rate (e.g., Mannucci et al. 2008 and references therein, Blanc et al. 2004, Hardin et al. 2000, and Cappellaro et al. 1997), the resultant Fe abundance is 2.9–14.5 solar, when considering only the SNe Ia contribution. Therefore, the expected SNe Ia contribution is sufficiently high to supply the Fe in the ISM of this galaxy.

As indicated from the optical line indices (Thomas et al. 2005; Bedregal et al. 2006; Bedregal et al. 2008), NGC 1316 may contain younger stellar populations. In this case, both the stellar mass loss rate and SN Ia rate might be higher (Ciotti et al. 1991; Ciotti & Ostriker 2007). The evolution of SN Ia rate is approximated by power-law model: $\propto t^{-1.3} L_B$ (Ciotti & Ostriker 2007; Greggio 2005), where $t$ is the age of stars. Then, assuming an age of 3 Gyr, the contribution of SNe Ia to the Fe abundance decreases by a factor of 0.7. Since a significant proportion of stars in NGC 1316 might be older than 3 Gyr, the effect of stellar age on the metal-enrichment by present SNe Ia would be less than a few tens of a percent. Then, the difference in the abundance pattern of the ISM of the early-type galaxies reflects the difference in the abundance pattern of the stars in the entire galaxy.

Since a longer star-formation time-scale yields more SNe Ia products in stars, the differences in the $\alpha$/Fe ratio in stars can constrain the star-formation histories. The abundance pattern of O, Ne, Mg, Si, and Fe in the ISM of NGC 1316 is close to that of the elliptical galax-
ies, have been obtained by Chandra, XMM, and Suzaku (e.g., Humphrey & Buote 2006, Werner et al. 2006, and Matsushita et al. 2007). We show the abundance patterns of NGC 4382, NGC 1332, NGC 720, NGC 1399, NGC 1404, NGC 4636, and NGC 5044, respectively (Nagino & Matsushita 2010, Humphrey et al. 2004, Tawara et al. 2008, Matsushita et al. 2007, Hayashi et al. 2009, Buote et al. 2003, and Konimaya et al. 2009) in figure 4. Considering the expected high contribution from the present SNe Ia, the observed solar abundance pattern in the ISM of NGC 1316 indicates an overabundance of $\alpha$/Fe in stars in the entire galaxy as in these elliptical galaxies, although optical observations indicate that stars in the central 1/10 $r_e$ region of NGC 1316 contain more SN Ia products than those in the giant elliptical galaxies (Thomas et al. 2005). Suzaku observed the ISM of the entire galaxy and revealed the abundance pattern in stars over the entire galaxy.

The abundance pattern of the S0 galaxy, NGC 4382, was also investigated with Suzaku (Nagino & Matsushita 2010). NGC 4382 is a normal S0 galaxy located on the outskirts of the Virgo cluster. Figure 4 also shows that the O/Fe ratio of the ISM in NGC 4382 is smaller, by a factor of two, as compared to that of NGC 1316. The different abundance patterns of these two S0 galaxies reflect a higher amount of SNe Ia products in the ISM of NGC 4382. Measurements of optical line indices indicate that stars in the most central region ($< 1/8 r_e$) of these two galaxies have similar $\alpha$/Fe ratios (Thomas et al. 2005; McDermid et al. 2006). As shown above, the effect of stellar age on the Fe abundance of the ISM from the present SNe Ia might be small, but stars in the entire NGC 4382 may contain more SNe Ia products than those in the entire NGC 1316. These results suggest differences in the metal enrichment histories and hence in the formation and evolution histories of the ISM in the merger remnant, NGC 1316, and the normal S0 galaxy, NGC 4382. Optical observations reveal that the $\alpha$/Fe ratio of the stars in the central regions of elliptical and S0 galaxies depends on the system mass (e.g., Thomas et al. 2005; Bedregal et al. 2008). The temperature of the ISM of NGC 4382 is about 0.3 keV (Nagino & Matsushita 2010) while those of NGC 1316 and the ellipticals are more than 0.5 keV, as shown in figure 4. Since the temperature of the ISM reflects the system mass, the differences in the abundance patterns in the ISM of the two galaxies may also reflect the dependence of the $\alpha$/Fe ratio of stars in the entire galaxy on the system mass. In addition, the abundance pattern of another S0 galaxy, NGC 1332 was searched with XMM and Chandra (Humphrey et al. 2004). Although the temperature of the ISM of NGC 1332 is $\gtrsim 0.5$ keV, the $\alpha$/Fe has large error to compare with other S0 galaxies, as shown in figure 4. Further studies to obtain, more samples of the elliptical and S0 galaxies with different ISM temperatures would enable us to understand the formation process of the early-type galaxies in more detail.

We thank the referee for providing valuable comments.

We gratefully acknowledge all members of the Suzaku hardware and software teams and the Science Working Group. SK is supported by JSPS Research Fellowship for Young Scientists.

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