Discovery of strong radiative recombination continua from IC443

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Abstract

We present the *Suzaku* detection of strong free-bound emission from the Galactic middle-aged supernova remnant (SNR) IC 443. A previous *ASCA* observation revealed that the Lyα fluxes of Si and S are significantly higher than those expected from the electron temperature of the bremsstrahlung continuum (Kawasaki et al. 2002). Therefore, it was claimed that the thermal plasma in this SNR is in "overionization". In the XIS spectrum of IC 443, we discovered hump-like features around at 2.7 and 3.5 keV as well as the strong Lyα lines. These humps are well represented by radiative recombination continua (RRC) of H-like Si and S with the electron temperature of $\sim$ 0.6 keV. The ionization temperatures of Si and S determined from the intensity ratios of the RRC to He-like Kα line are $\sim$ 1.0 keV and $\sim$ 1.2 keV, respectively. We thus find firm evidence for an extremely-overionized (recombining) plasma. As the origin of the overionization, a thermal conduction scenario argued in the previous work is not favored in our new results. We propose that the highly-ionized gas were made at the initial phase of the SNR evolution in dense regions around a massive progenitor, and the low electron temperature is due to a rapid cooling by an adiabatic expansion.

Key words: ISM: supernova remnants — radiation mechanisms: thermal

1. Introduction

IC 443 (G189.1+3.0), a Galactic supernova remnant (SNR) at a distance of 1.5 kpc (Welsh & Sallmen 2003), is located near the Gem OB1 association and a dense giant molecular cloud (Cornett et al. 1977) with OH maser emission (Claussen et al. 1997). These facts strongly suggest that the remnant originated from a collapse of a massive progenitor. Braun & Strom (1986) proposed that the shock wave has expanded into the pre-existing wind-blown bubble shell. This was confirmed by a kinematical study of the optical filaments (Meaburn et al. 1990). A comprehensive X-ray study of IC 443 was first made with the *Einstein* and *HEAO-A2* satellites (Petre et al. 1988). They estimated the SNR age to be $\sim$3000 yr. Recently, Troja et al. (2008) derived the age of $\sim$4000 yr from the morphologies of the shocked ejecta and interstellar medium (ISM) revealed by *XMM-Newton.* Thus, IC 443 is a middle-aged SNR.

Using *ASCA*, Kawasaki et al. (2002) found that the ionization degrees of Si and S were significantly higher than those expected from the electron temperature of the bremsstrahlung continuum. Therefore, it was argued that the plasma is in overionization ($kT_z > kT_e$, where kT_z and kT_e are ionization and electron temperatures, respectively). On the other hand, *XMM-Newton* found that the plasma is in collisional ionization equilibrium (CIE), or the overionization is only marginal (Troja et al. 2008). These two controversial results hinge upon small differences, if any, between the estimated electron and ionization temperatures.

Our purpose is to investigate whether the overionized plasma is really present or not, by utilizing the superior spectral capabilities of X-ray Imaging Spectrometers (XIS: Koyama et al. 2007) on board the *Suzaku* satellite. If present, we will study the plasma condition quantitatively to discuss the possible origin of the overionization. The details of the observation and data reduction are found in Yamaguchi et al. (2009).

2. Analysis and Results

We extracted the representative spectrum from the brightest region in the SNR, the rectangular with an angular size of $7' \times 5'$, which approximately corresponds to the "Center" region of Kawasaki et al. (2002). The XIS spectra of the two FIs were made by subtracting the non X-ray background (NXB), and were merged to improve

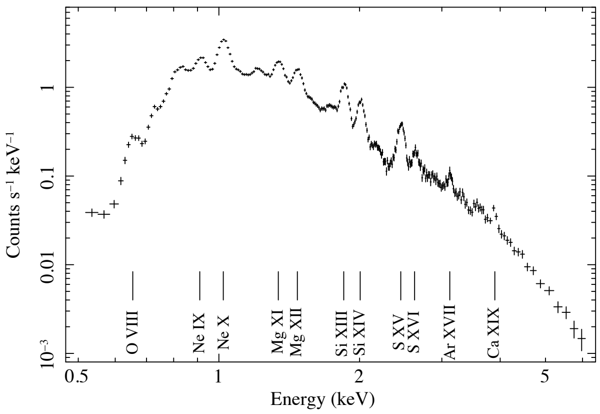

Fig. 1. Full-band XIS-FI spectrum. The energies of prominent Kα emission lines from specific elements are labeled in the panel.

the statistics. Figure 1 shows the resultant spectrum. We can see several prominent lines of Kα emission from He- and H-like ions (hereafter, Heα and Lyα). In order to examine the ionization states of Si and S, we hereafter focus on the spectrum in the energy range above 1.75 keV (Fig. 2). For simplicity, the BI spectrum is not shown in the figures, although it was analyzed simultaneously with the FI.

We first fitted the spectrum with a model of a thin-thermal plasma in CIE state (a VAPEC model: Smith et al. 2001). The abundances (Anders & Grevesse 1989) of Si, S, and Ar were free parameters, while the Ca abundance was tied to Ar. Interstellar extinction was fixed to a hydrogen column density of $N_{\rm H} = 7 \times 10^{21}$ cm^{-2} with the solar elemental abundances, following Kawasaki et al. (2002) and Troja et al. (2008). The cosmic X-ray background (CXB) spectrum was approximated by a power-law model with photon index of $\Gamma = 1.412$ and the surface brightness in the 2–10 keV band of 6.4×10^{-8} erg cm^{-2} s^{-1} sr^{-1} (Kushino et al. 2002). This fit leaved large residuals at the energies of S and Ar Lyα lines, and hence was rejected with the χ^2/dof of 935/270.

We, therefore, applied a model of one-temperature VAPEC (CIE plasma) plus narrow Gaussian lines at 2006, 2623, and 3323 eV, the Lyα energies of the Si, S, and Ar hydrogenic ions, respectively. This process is essentially the same as Kawasaki et al. (2002). Lyβ lines of the same elements were also added, but they were not significant except for Si (2377 eV). The result is shown in Figure 2a, with the best-fit CIE plasma temperature of $kT_e \sim 0.94$ keV. Although the χ^2/dof value was significantly reduced to 657/266, the model was still unacceptable. In fact, apparent hump-like residuals are found around ~2.7 keV and ~3.5 keV. No additional CIE component nor non-equilibrium ionization (NEI) plasma model removed these hump-like residuals.

At the energies of the humps, no emission line candidate from an abundant element is found. However, the energies are consistent with the K-shell binding potentials (I_z) of the H-like Si (2666 eV) and S (3482 eV). Therefore, the humps are likely due to the free-bound transitions to the K-shell of the H-like Si and S. When the electron temperature is much lower than the K-edge energy ($kT_e \ll I_z$), a formula for the radiative recombination continuum (RRC) spectrum is approximated as;

$$\frac{dP}{dE}(E_\gamma) \propto \exp\left(-\frac{E_\gamma - I_z}{kT_e}\right), \quad \text{for } E_\gamma \geq I_z \ . \qquad (1)$$

We added the RRC of Equation 1 for H-like[1] Si and S. The kT_e values of the RRC were linked to that of the VAPEC component. Then, the fit was dramatically improved to an acceptable χ^2/dof of 290/264. Although the hump-like residuals were completely removed by this fit, we further added the RRC model of H-like Mg. This step

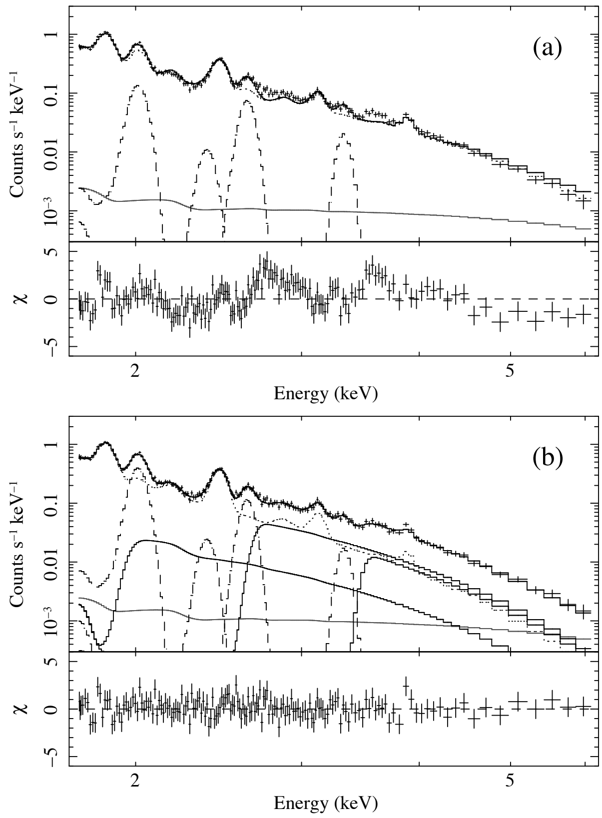

Fig. 2. (a) XIS-FI spectrum in the 1.75–6.0 keV band. The best-fit VAPEC model is given with the dotted line, and additional Gaussians for the Lyman lines of Si, S, and Ar are shown with the dashed lines. The CXB is represented by the gray solid line. The lower panel shows the residual from the best-fit model. The hump-like features are clearly found around the energies of ~2.7 keV and ~3.5 keV. (b) Same spectrum as (a), but for a fit with RRC components of H-like Mg, Si, and S (black solid lines). The residuals seen in (a) are disappeared.

*1 "H-like RRC" refers to the free-bound emission due to electron captures by fully-ionized ions into ground state of H-like ions

Table 1. Best-fit spectral parameters

Component	Parameter		Value
CIE (VAPEC)	kT_e (keV)		0.61 (0.59–0.64)
	Z_{Si} (solar)		0.82 (0.78–0.85)
	Z_{S} (solar)		1.7 (1.6–1.8)
	Z_{Ar} (solar)		2.5 (2.2–2.8)
	VEM (10^{12} cm^{-5})[a]		6.4 (6.3–6.6)
		E (keV)[b]	Flux (10^{-4} photon cm^{-2} s^{-1})
Line	Si Lyα	2.006	2.8 (2.7–2.9)
	Si Lyβ	2.377	0.21 (0.14–0.29)
	S Lyα	2.623	0.84 (0.79–0.90)
	Ar Lyα	3.323	0.11 (0.085–0.14)
RRC	H-like Mg	1.958	1.2 (1.0–1.5)
	H-like Si	2.666	2.2 (2.0–2.3)
	H-like S	3.482	0.46 (0.41–0.51)

The uncertainties in the parentheses are the 90% confidence range. [a]Volume emission measure, $\int n_e n_p \, dV/(4\pi D^2)$, where n_e, n_p, V, and D are the electron and proton densities (cm^{-3}), the emitting volume (cm^3), and the distance to the source (cm), respectively. [b]The fixed energy values of the line center or the K-edge.

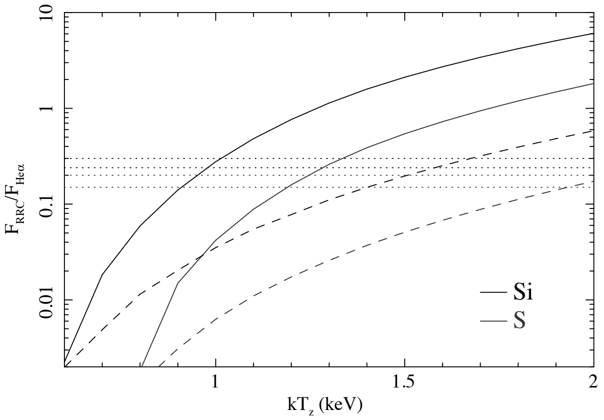

Fig. 3. Emissivity ratios of H-like RRC to He-like Kα lines as a function of ionization temperature (kT_z), predicted by the plasma radiation code of Masai (1994) for recombining plasma with electron temperature (kT_e) of 0.6 keV. Black and gray solid lines represent Si and S, respectively. For comparison, the same ratios for CIE ($kT_z = kT_e$) plasma (the APEC model: Smith 2001) are indicated by dashed lines. The horizontal dotted lines represent the 90% upper and lower limits of the observed values.

is reasonable because Mg is more abundant than Si and S in the solar abundance ratio of Anders & Grevesse (1989) and the K-edge energy of H-like Mg ($I_z = 1958$ eV) falls into the analyzed band. The χ^2/dof value was significantly reduced to 267/263, which gives an F-test probability of $\sim 3 \times 10^{-6}$. The best-fit parameters and model are given in Table 1 and Figure 2b, respectively.

3. Discussion and Conclusion

We have found that the 1.75–6.0 keV spectrum cannot be represented with CIE nor NEI plasma alone, but need the additional fluxes of the Lyman lines and the H-like RRC of Si and S (and possibly Mg). This is the first detection of clear RRC emissions in an SNR. In the following, we quantitatively discuss the implications of our spectral results.

From the best-fit model in Table 1, the flux ratios of H-like RRC to He-like Kα (Heα) line ($F_{\mathrm{RRC}}/F_{\mathrm{He\alpha}}$) are given to be 0.28 (0.24–0.30) and 0.18 (0.15–0.20) for Si and S, respectively. These are compared, in Figure 3, with the modeled emissivity ratios by the plasma radiation code of Masai (1994) for the electron temperature of 0.6 keV. We find that the large observed ratios of $F_{\mathrm{RRC}}/F_{\mathrm{He\alpha}}$ are significantly above those in the CIE case ($kT_z = kT_e$), but can be reproduced in the overionization case ($kT_z > kT_e$). The ionization temperatures of Si and S are determined to be ~ 1.0 keV and ~ 1.2 keV, respectively. This is, therefore, the firm evidence of the overionized (recombining) plasma.

The elemental abundances in Table 1 are determined as the parameters of the 0.6 keV VAPEC (CIE) component, and hence should be modified in the real case of the overionized plasma. The intensity of the Si-Heα line is given as $F_{\mathrm{He\alpha}} \propto \varepsilon(T_e) \cdot f_{\mathrm{He}}(T_z) \cdot Z_{\mathrm{Si}}$, where $\varepsilon(T_e)$ and $f_{\mathrm{He}}(T_z)$ are, respectively, emissivity coefficient for electron temperature T_e and fraction of He-like ion for ionization temperature T_z. The abundance, therefore, can be modified by the fraction ratio of He-like ions, $f_{\mathrm{He}}(0.6 \text{ keV})/f_{\mathrm{He}}(1.0 \text{ keV})$. According to the ionization population calculations by Mazzotta (1998), the ion fractions of He-like, H-like, and fully-ionized Si ($f_{\rm He}$, $f_{\rm H}$, f_0) are estimated to be (0.83, 0.15, 0.01) for $kT_z = 0.6$ keV and (0.37, 0.43, 0.19) for $kT_z = 1.0$ keV, respectively. Then, the modified $Z_{\rm Si}$ is $0.82 \times (0.83/0.37) \simeq 2.2$ solar. For S, ($f_{\rm He}$, $f_{\rm H}$, f_0) are (0.91, 0.02, 0) for $kT_z = 0.6$ keV and (0.59, 0.32, 0.06) for $kT_z = 1.2$ keV. Thus, we similarly modified $Z_{\rm S}$ to be $1.7 \times (0.91/0.59) \simeq 2.6$ solar.

Using the measured RRC flux, we can independently determine the volume emission measure, VEM = $\int n_e n_p \, dV/(4\pi D^2)$, from a following equation:

$$F_{\rm RRC} = \alpha_1(T_e) \cdot n_Z/n_p \cdot f_0 \cdot {\rm VEM} \ , \quad (2)$$

where $\alpha_1(T_e)$ and n_Z are K-shell RRC rate coefficient for electron temperature T_e and number density of element Z, respectively. According to Badnell (2006), we find total radiative recombination rate for fully-ionized Si, at $kT_e = 0.6$ keV, is $\alpha_{\rm tot} \sim 2.3 \times 10^{-12}$ cm^3 s^{-1}. Since the rate of the recombination into a level of principal quantum number n is described as;

$$\alpha_n \propto \frac{1}{n^3} \left(\frac{3}{2} \frac{kT_e}{I_z} + \frac{1}{n^2} \right)^{-1} \quad (3)$$

(e.g., Nakayama & Masai 2001), we obtain $\alpha_1/\alpha_{\rm tot} = 0.65$, for $kT_e = 0.6$ keV and $I_z = 2.666$ keV. Thus, the VEM is calculated to be $\sim 9.9 \times 10^{12}$ ($Z_{\rm Si}$/2.2 solar)$^{-1}$ (f_0/0.19)$^{-1}$ cm^{-5}. Similarly, $\alpha_{\rm tot}$ at 0.6 keV for fully-ionized S is derived to be $\sim 3.2 \times 10^{-12}$ cm^3 s^{-1}. Therefore, the RRC flux of S corresponds to the VEM of $\sim 9.4 \times 10^{12}$ ($Z_{\rm S}$/2.6 solar)$^{-1}$ (f_0/0.06)$^{-1}$ cm^{-5}. These values are almost consistent with that of the VAPEC component (Table 1).

The angular size of the spectrum extraction region corresponds to 3.1×2.2 pc^2 at $D = 1.5$ kpc. Assuming the plasma depth of 3 pc, the emitting volume is estimated to be 6.1×10^{56} cm^3. Therefore, the VEM of 6.6×10^{12} cm^{-5} is converted to the uniform electron density of $n_e \sim 1.7$ cm^{-3}.

The overionization claim for IC 443 was first argued by Kawasaki et al. (2002) based on *ASCA* data. As the mechanism to form the overionized plasma, they proposed that the SNR consists of a central hot ($kT_e \sim$ 1.0 keV) region surrounded by a cool ($kT_e \sim 0.2$ keV) outer shell, and interpreted that the hot interior cooled down via thermal conduction to the cool exterior. Under the several reasonable boundary conditions, they estimated the cooling time from $kT_e = 1.5$ keV to 1.0 keV is about (3–10) $\times$ 10^3 yr, roughly the same as the SNR age (∼4000 yr: Troja et al. 2008). However, this scenario cannot work on our new results. According to equation (5) of Kawasaki et al. (2002), the conduction timescale is estimated to be

$$t_{\rm cond} \simeq 3.9 \times 10^4 \left(\frac{n_e}{1.7 \ {\rm cm}^{-3}} \right) \left(\frac{kT_e}{0.6 \ {\rm keV}} \right)^{-5/2} {\rm yr} \ , \quad (4)$$

for the similar boundary condition. Thus, cooling via conduction requires far longer time than the SNR age.

Since the progenitor of IC 443 has been suggested to be a massive star with strong stellar wind activity (Braun & Strom 1986; Meaburn et al. 1990), we propose another possibility that the rapid and drastic cooling is due to a rarefaction process, as discussed by Itoh & Masai (1989). If a supernova explodes in a dense circumstellar medium made in the progenitor's super giant phase, the gas is shock-heated to high temperature and significantly ionized at the initial phase of the SNR evolution. Subsequent outbreak of the blast wave to a low-density ISM caused drastic adiabatic expansion of the shocked gas and resultant rapid cooling of the electrons. The lifetimes of the fully-stripped ions are roughly estimated to be $\tau = (\alpha_{\rm tot} n_e)^{-1} \simeq 8.1 \times 10^3 (n_e/1.7{\rm cm}^{-3})^{-1}$ yr for Si and $\simeq 5.8 \times 10^3 (n_e/1.7{\rm cm}^{-3})^{-1}$ yr for S, respectively. Note that these values are underestimated compared to the actual timescale for the plasma to reach CIE, because the contribution of collisional ionization processes is ignored. Nevertheless, the estimated lifetimes are longer than the age of IC 443. The overionized plasma can, therefore, still survive at present.

Future observations with very high energy resolution like the *Astro-H* mission will give firm evidence for the RRC structure not only on Si and S but also on the other major elements. This will provide more quantitative study on the peculiar SNR IC 443.

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