DISCOVERY OF STRONG RADIATIVE RECOMBINATION CONTINUUM FROM THE SUPERNOVA REMNANT IC 443 WITH SUZAKU

H. Yamaguchi\textsuperscript{1}, M. Ozawa\textsuperscript{2}, K. Koyama\textsuperscript{3}, K. Masa\textsuperscript{3}, J. S. Hiraga\textsuperscript{1}, M. Ozaki\textsuperscript{4}, and D. Yonetoku\textsuperscript{5}

\textsuperscript{1} RIKEN (The Institute of Physical and Chemical Research), 2-1 Hirosawa, Wako, Saitama 351-0198, Japan; hiroya@crab.riken.jp
\textsuperscript{2} Department of Physics, Kyoto University, Kitashirakawa-oiwake-cho, Sakyo-ku, Kyoto 606-8502, Japan
\textsuperscript{3} Department of Physics, Tokyo Metropolitan University, 1-1 Minami-Osawa, Hachioji, Tokyo 192-0397, Japan
\textsuperscript{4} Institute of Space and Astronomical Science, JAXA, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan
\textsuperscript{5} Department of Physics, Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan

\textit{Received 2009 May 18; accepted 2009 September 18; published 2009 October 7}

ABSTRACT

We present the \textit{Suzaku} spectroscopic study of the Galactic middle-aged supernova remnant (SNR) IC 443. The X-ray spectrum in the 1.75–6.0 keV band is described by an optically thin thermal plasma with the electron temperature of \(~0.6\) keV and several additional Lyman lines. We robustly detect, for the first time, strong radiative recombination continua (RRC) of H-like Si and S around at 2.7 and 3.5 keV. The ionization temperatures of Si and S determined from the intensity ratios of the RRC to He-like K\textalpha\ lines are \(~1.0\) keV and \(~1.2\) 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 previous work is not favored in our new results. We propose that the highly ionized gas was 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.

\textbf{Key words:} ISM: individual (IC 443) – radiation mechanisms: thermal – supernova remnants – X-rays: ISM

1. INTRODUCTION

IC 443 (G189.1+3.0), a Galactic supernova remnant (SNR) at a distance of 1.5 kpc (Welsh & Salln\textsuperscript{4} 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 \textit{Einstein} and \textit{HEAO-A2} satellites (Petre et al. 1988). They estimated the SNR age to be \(~3000\) yr. Recently, Troja et al. (2008) derived the age of \(~4000\) yr from the morphologies of the shocked ejecta and interstellar medium (ISM) revealed by \textit{XMM-Newton}. Thus, IC 443 is a middle-aged SNR.

Using \textit{Suzaku}, 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 \((kTz > kTe)\), where \(kTz\) and \(kTe\) are ionization and electron temperatures, respectively. On the other hand, Troja et al. (2008) found that the plasma is in collisional ionization equilibrium (CIE), or the overionization is only marginal based on \textit{XMM-Newton} data. These two controversial results hinge upon small differences, if any, between the estimated electron and ionization temperatures.

In this Letter, we investigate whether the overionized plasma is really present or not, by utilizing the superior spectral capabilities for diffuse sources of X-ray Imaging Spectrometers (XIS: Koyama et al. 2007) aboard the \textit{Suzaku} satellite (Mitsuda et al. 2007). If present, we will study the plasma condition quantitatively to discuss the possible origin of the overionization.

2. OBSERVATION AND DATA REDUCTION

The northern part of IC 443 was observed with \textit{Suzaku} on 2007 March 6 (Observation ID = 501006010). Three XISs

\textsuperscript{4} \textit{Suzaku} carried four XISs, but one is now out of operation due to a damage possibly by an impact of a micro-meteorite.

\textsuperscript{5} http://heasarc.nasa.gov/docs/suzaku/processing/criteria_xis.html
energy scale. 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 (Figure 3). Detailed studies including the lower energies will be reported in a separate paper.

We first fitted the spectrum with a model of a thin-thermal plasma in CIE state (a VAPEC model). 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 $N_{\text{H}} = 7 \times 10^{21}$ 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 a photon index of $\Gamma = 1.412$ and the surface brightness in the 2–10 keV band of $6.4 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$ (Kushino et al. 2002). Since IC 443 is located in the anti-Galactic center direction, contribution of the Galactic ridge X-ray emission was ignored. In the initial fit, we found a significant inconsistency between the FI and BI data around the energy of neutral Si K-edge (1.84 keV). This is due to the well-known calibration issue of the XIS. Since the calibration for the FI CCDs is currently far better than the BI, we decided to ignore the energy band below 1.9 keV in the BI spectrum. This fit left several large residuals, in both spectra, at the energies of S and Ar Ly$\alpha$ lines, and hence was rejected with the $\chi^2$/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 Ly$\alpha$ energies of the Si, S, and Ar, hydrogenic ions, respectively. This process is essentially the same as Kawasaki et al. (2002). Ly$\beta$ lines of the same elements were also added, but they were not significant except for Si (2377 eV). The result is shown in Figure 3(a), with the best-fit CIE plasma temperature of $kT_e \sim 0.94$ keV. Although the $\chi^2$/dof value was significantly reduced to 657/266, the model was still unacceptable. In fact, apparent hump-like residuals are found around $\sim 2.7$ keV and $\sim 3.5$ keV, in addition to the systematic model excess in the continuum at the energies above $\sim 4.5$ keV.

We checked systematic error due to the CXB fluctuation by allowing the CXB intensity as a free parameter. The fit, however, did not improve at all. We also tried two-component VAPEC models with independent temperatures and abundances, but these were rejected with $\chi^2$/dof = 737/265. The results were essentially the same as Figure 3(a); the hump-like residuals remained at $\sim 2.7$ keV and $\sim 3.5$ keV. No additional CIE component nor non-equilibrium ionization (NEI) plasma model removed the hump-like residuals with significant improvement of the $\chi^2$ value.

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 ($I_e$) 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. A formula for the spectrum of radiative recombination continuum (RRC) is found in Equation (21) of Smith & Brickhouse (2002). When the electron temperature is much lower than the K-edge energy ($kT_e \ll I_e$), this formula is approximated as

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

Thus, the width of the RRC structure depends on the electron temperature. We added the RRC of Equation (1) for H-like$^8$ 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 $\chi^2$/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 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 ($I_e = 1958$ eV) falls into the analyzed band. The $\chi^2$/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 3(b), respectively.

The spectrum was also fitted with the independent electron temperatures for the VAPEC and RRC components, but the values are consistent with each other within their statistical uncertainties.

4. 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 $^8$H-like RRC refers to the free-bound emission due to electron captures by fully ionized ions into ground state of H-like ions.
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 lines (\(F_{\text{RRC}}/F_{\text{Heα}}\)) 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 4, with the modeled emissivity ratios by the plasma radiation code of Masai (1994) for recombining plasma with electron temperature (\(kT_e\)) of 0.6 keV. However, since the RRC process is accompanied with electron captures to the excited levels, as given in Equation (3), the resulting cascade decay to the ground state contributes the line emission. In a CIE plasma, on the other hand, origins of the line emissions are more dominated by the collisional excitation. Therefore, a \(kT_e\) determination done by comparing with a CIE plasma code is not a proper method. Also, the previous works assumed that the continuum spectrum purely consists of bremsstrahlung emission, and determined \(kT_e\) to be \(\sim 1.0\) keV. This value has been reduced owing to the discovery of the strong RRC emissions.

It should be noted that the elemental abundances in Table 1 are determined as the parameters of the 0.6 keV V APEC (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

\[
F_{\text{Heα}} \propto \varepsilon(T_e) \cdot f_{\text{He}}(T_e) \cdot Z_{\text{Si}},
\]

where \(\varepsilon(T_e)\) and \(f_{\text{He}}(T_e)\) 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 to be \(\sim 1.5\) keV from the S Lyα/Heα flux ratio compared with the predicted emissivity ratio in the CIE plasma code. Troja et al. (2008) adopted the same analysis procedure to the XMM-Newton spectrum, and claimed that \(kT_e\) obtained from the line flux ratio was nearly same as the bremsstrahlung temperature (\(kT_z\)).

Figure 4. 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 red solid lines represent Si and S, respectively. For comparison, the same ratios for CIE (\(kT_e = kT_z\)) plasma (the APEC model: Smith et al. 2001) are indicated by dashed lines. The horizontal dotted lines represent the 90% upper and lower limits of the observed values.

Figure 3. (a) XIS spectrum in the 1.75–6.0 keV band. Black and red represent FI and BI, respectively. Individual components of the best-fit model for the FI data are shown with solid colored lines: blue, green, and gray are the V APEC, Gaussians (Si-Lyα, Si-Lyβ, S-Lyα, and Ar-Lyα), and CXB, respectively. The lower panel shows the residual from the best-fit model. Two hump-like features are clearly found around the energies of \(\sim 2.7\) keV and \(\sim 3.5\) keV. (b) Same spectrum as (a), but for a fit with RRC components of H-like Mg, Si, and S (magenta lines). The residuals seen in (a) are disappeared.

Table 1

| Component | Parameter | Value |
|-----------|-----------|-------|
| CIE (V APEC) | \(kT_e\) (keV) | 0.61 (0.59–0.64) |
| Z ⊙ (solar) | 0.82 (0.78–0.85) |
| Z ⊙ (solar) | 1.7 (1.6–1.8) |
| Z ⊙ (solar) | 2.5 (2.2–2.8) |
| VEM (10^{12} cm^{-5}) | 6.4 (6.3–6.6) |
| Additional components | \(E\) (keV) | Flux |
| Line | \(E\) (keV) | Flux |
| 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) |

Notes. The uncertainties in the parentheses are the 90% confidence range.

* Volume emission measure, \(\int n_e n_p dV/(4\pi D^2)\), where \(n_e, n_p, V, D\) are the electron and proton densities (cm\(^{-3}\)), the emitting volume (cm\(^4\)), and the distance to the source (cm), respectively.

* The fixed energy values of the line center or the K-edge.

* Total flux in the unit of \(10^{-14}\) photon cm\(^{-2}\) s\(^{-1}\).
of He-like ions, \( f_{\text{He}}(0.6 \text{ keV})/f_{\text{He}}(1.0 \text{ keV}) \). According to the ionization population calculations by Mazzotta et al. (1998), the ion fractions of He-like, H-like, and fully ionized Si (\( f_{\text{He}}, f_{\text{H}}, f_{\text{Si}} \)) are estimated to be (0.83, 0.15, 0.01) for \( kT_e = 0.6 \text{ keV} \) and (0.37, 0.43, 0.19) for \( kT_e = 1.0 \text{ keV} \), respectively. Then, the modified \( Z_\text{S} \) is \( 0.82 \times (0.83/0.37) \approx 2.2 \) solar. For S, \( (f_{\text{He}}, f_{\text{H}}, f_{\text{Si}}) \) are (0.91, 0.02, 0) for \( kT_e = 0.6 \text{ keV} \) and (0.59, 0.32, 0.06) for \( kT_e = 1.2 \text{ keV} \). Thus, we similarly modified \( Z_\text{S} \) to be 1.7 \times (0.91/0.59) \approx 2.6 \) solar.

Using the measured RRC flux, we can independently determine the volume emission measure (VEM) as

\[
F_{\text{RRC}} = \alpha_1(T_e) \cdot n_Z/n_p \cdot f_0 \cdot \text{VEM},
\]

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 that the total radiative recombination rate for fully ionized Si, at \( kT_e = 0.6 \text{ keV} \), is \( \alpha_{\text{tot}} \sim 2.3 \times 10^{-12} \text{ cm}^3 \text{s}^{-1} \). Since the rate of the recombination into a level of principal quantum number \( n \) is described as

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

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

The rectangular region in Figure 1 corresponds to \( 3.1 \times 2.2 \text{ pc}^2 \) at \( D = 1.5 \text{ kpc} \). Assuming the plasma depth of 3 pc, the emitting volume is estimated to be \( 6.1 \times 10^{60} \text{ cm}^3 \). Therefore, the VEM of \( 6.0 \times 10^{12} \text{ cm}^{-5} \) is converted to the uniform electron density of \( n_e \sim 1.7 \text{ cm}^{-3} \).

As the mechanism to form the ionized plasma, Kawasaki et al. (2002) proposed that the SNR consists of a central hot (\( kT_e \sim 1.0 \text{ keV} \)) region surrounded by a cool (\( kT_e \sim 0.2 \text{ keV} \)) 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 \( kT_e = 1.5 \text{ keV} \) to 1.0 keV is about \( (3-10) \times 10^3 \text{ yr} \), roughly the same as the SNR age (\( \approx 4000 \text{ yr} \); 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

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

if the similar boundary condition is assumed. Thus, cooling via conduction requires far longer time than the SNR age. Photoionization is also unlikely because no strong ionizing source is found. Furthermore, the temperature of \( \approx 0.6 \text{ keV} \) is significantly higher than that of a typical photoionization plasma (\( \lesssim 0.1 \text{ keV} \); e.g., Kawashima & Kitamoto 1996).

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 \( \tau = (\alpha_{\text{tot}} n_e) \sim 8.1 \times 10^3 (n_e/1.7 \text{ cm}^{-3})^{-1} \text{ yr} \) for Si and \( \approx 5.8 \times 10^3 (n_e/1.7 \text{ cm}^{-3})^{-1} \text{ yr} \) 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.

The authors deeply appreciate constructive suggestions from the referee, Randall Smith. We are also grateful to Kazuo Makishima and Aya Bamba for helpful discussions, and Ehud Behar for useful comments. H.Y. and J.S.H. are supported by the Special Postdoctoral Researchers Program in RIKEN. M.O. is a Research Fellow of Japan Society for the Promotion of Science (JSPS). This work is partially supported by the Grant-in-Aid for the Global COE Program “The Next Generation of Physics, Spun from Universality and Emergence,” Young Scientists (HY), and Challenging Exploratory Research (KK) from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.

REFERENCES

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Badnell, N. R. 2006, ApJS, 167, 334
Braun, R., & Strom, R. G. 1986, A&A, 164, 193
Claussen, M. J., Frail, D. A., Goss, W. M., & Gaume, R. A. 1997, ApJ, 489, 143
Clemett, R. H., Chin, G., & Knapp, G. R. 1977, A&A, 54, 889
Itoh, H., & Masai, K. 1989, MNRAS, 236, 885
Kawasaki, M. T., Ozaki, M., Nagase, F., Masai, K., Ishida, M., & Petre, R. 2002, ApJ, 572, 897
Kawashima, K., & Kitamoto, S. 1996, PASJ, 48, L113
Koyama, K., et al. 2007, PASJ, 59, 23
Kushino, A., Ishisaki, Y., Morita, U., Yamasaki, N. Y., Ishida, M., Ohashi, T., & Ueda, Y. 2002, PASJ, 54, 327
Masai, K. 1994, ApJ, 437, 770
Mazzotta, P., Mazzitelli, G., Colafrancesco, S., & Vittorio, N. 1998, A&AS, 133, 403
Meaburn, J., Whitehead, M. J., Raymond, J. C., Clayton, C. A., & Marston, A. P. 1990, A&A, 227, 191
Mitsuda, K., et al. 2007, PASJ, 59, 1
Nakayama, M., & Masai, K. 2001, A&A, 375, 328
Petre, R., Szymkowiak, A. E., Seward, F. D., & Willingale, R. 1988, ApJ, 335, 215
Serlemitsos, P. J., et al. 2007, PASJ, 59, 9
Smith, R. K., Brickhouse, N. S., Liedahl, D. A., & Raymond, J. C. 2001, ApJ, 556, L91
Smith, R. K., & Brickhouse, N. S. 2002, Physics Underlying the ATOMDB (Cambridge, MA: Chandra X-Ray Center), http://cxc.harvard.edu/atomdb/physics/plasma/plasma.html
Troja, E., Bocchino, F., Miceli, M., & Reale, F. 2008, A&A, 485, 777
Uchiyama, H., et al. 2009, PASJ, 61, 9
Welsh, B. Y., & Sallmen, S. 2003, A&A, 408, 545