Investigation of the Physical Origin of Overionized Recombining Plasma in the Supernova Remnant IC 443 with XMM-Newton

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Abstract

The physical origin of the overionized recombing plasmas (RPs) in supernova remnants (SNRs) has been attracting attention because its understanding provides new insight into SNR evolution. However, the process of the overionization, although it has been discussed in some RP-SNRs, is not yet fully understood. Here, we report on spatially resolved spectroscopy of X-ray emission from IC 443 with XMM-Newton. We find that RPs in regions interacting with dense molecular clouds tend to have lower electron temperature and lower recombination timescale. These tendencies indicate that RPs in these regions are cooler and more strongly overionized, which is naturally interpreted as a result of rapid cooling by the molecular clouds via thermal conduction. Our result on IC 443 is similar to that on W44 showing evidence for thermal conduction as the origin of RPs at least in older remnants. We suggest that evaporation of clumpy gas embedded in a hot plasma rapidly cools the plasma as was also found in the W44 case. We also discuss if ionization by protons accelerated in IC 443 is responsible for RPs. Based on the energetics of particle acceleration, we conclude that the proton bombardment is unlikely to explain the observed properties of RPs.

Unified Astronomy Thesaurus concepts: Supernova remnants (1667); X-ray astronomy (1810); Plasma astrophysics (1261); Molecular clouds (1072)

1. Introduction

X-ray spectroscopy of supernova remnants (SNRs) enables us to investigate the thermal properties of SNR plasmas, providing information on their evolution history. Recent X-ray observations unveiled the presence of plasmas in a recombination-dominant state in a dozen SNRs (e.g., Ozawa et al. 2009), including the target of the present work, IC 443 (Yamaguchi et al. 2009). Such plasmas have a higher degree of ionization than that expected in collisional ionization equilibrium (CIE), and thus often called overionized recombining plasmas (RPs). RPs were not anticipated in the previously accepted scenario that SNR plasmas are collisionally ionized until they reach equilibrium. The physical origin of the overionization has been attracting attention because it reveals important processes not considered in the standard scenario (e.g., Zhang et al. 2019).

The formation process of RPs is thought to be closely related to interaction between the SNRs and ambient clouds, and two distinct scenarios have mainly been considered. One model is the thermal conduction scenario, which is based on an idea originally proposed by Kawasaki et al. (2002, 2005). Some authors, e.g., Matsumura et al. (2017), Okon et al. (2018), and Katsuragawa et al. (2018), who analyzed Suzaku data of G166+4.3, W28, and CTB 1, respectively, claimed that thermal conduction by ambient clouds cools their X-ray plasmas and makes the overionization. Carrying out spatially resolved spectroscopy of X-ray emission of W44 with XMM-Newton, Okon et al. (2020) investigated spatial variations of the electron temperature and the degree of overionization of the RP, and presented clear evidence for the thermal conduction scenario.

Another plausible scenario is rarefaction, predicted by Itoh & Masai (1989) and Shimizu et al. (2012), where rapid adiabatic expansion is responsible for the overionization. Observational results on W49B preferring this scenario are reported by some authors, e.g., Miceli et al. (2010), Lopez et al. (2013), and Holland-Ashford et al. (2020), although they are questioned by Sano et al. (2021) based on recent Atacama Large Millimeter/submillimeter Array data. Yamaguchi et al. (2018), who performed spatially resolved spectroscopy of the remnant with the Nuclear Spectroscopic Telescope Array revealed obvious spatial variations of RP parameters, which are naturally explained by the rarefaction scenario. Although both mechanisms could be responsible for RPs, the number of SNRs with such spatial-spectral analysis as demonstrated by Yamaguchi et al. (2018) and Okon et al. (2020) that has been applied is still limited so that the formation process of RPs in SNRs is not comprehensively understood.

IC 443 (a.k.a., G189.1+3.0) has been regarded as one of the most important SNRs for studies of RPs. IC 443 is a Galactic core-collapse SNR at a distance of ~1.5 kpc (Welsh & Sallmen 2003) toward the Galactic anticenter. Possible signatures of RPs were first suggested by Kawasaki et al. (2002) by measuring the HeII/HeI ratio of Si and S with the Advanced Satellite for Cosmology and Astrophysics. Yamaguchi et al. (2009) discovered radiative recombinig continua (RRCs) of Si and S in Suzaku data, and showed the first unequivocal evidence of an RP in SNRs, along with the W49B case by Ozawa et al. (2009). Subsequent Suzaku observations revealed that heavier ions such as Ca and Fe are also in the overionized state (Ohnishi et al. 2014). IC 443 is known to be interacting with dense clouds through detections of 12CO lines.
Table 1
Observation Log

| Target     | Obs. ID      | Obs. Date   | (R.A., Decl.)                  | Effective Exposure (ks) |
|------------|--------------|-------------|--------------------------------|-------------------------|
| IC 443     | 0114100101   | 2000 Sep 26 | (6°17′29′′, +22°41′44.0″)      | 11                      |
| IC 443     | 0114100201   | 2000 Sep 25 | (6°16′14.99, +22°41′60.0″)     | 5                       |
| IC 443     | 0114100301   | 2000 Sep 27 | (6°17′29′′, +22°25′14.0″)      | 22                      |
| IC 443     | 0114100401   | 2000 Sep 28 | (6°16′14.99, +22°18′02.5″)     | 23                      |
| IC 443     | 0114100501   | 2000 Sep 25 | (6°17′29′′, +22°41′60.0″)      | 15                      |
| IC 443     | 0114100601   | 2000 Sep 27 | (6°17′29′′, +22°25′14.0″)      | 4                       |
| IC 443     | 0301960101   | 2006 Mar 30 | (6°18′04.99, +22°27′33.0″)     | 46                      |
| IC 443     | 0600110101   | 2010 Mar 17 | (6°17′06.00, +22°43′24.0″)     | 26                      |

Note.

a Equinox in J2000.0.

Figure 1. MOS+pn images of IC 443 in the energy band of (a), (b) 0.5–4.0 keV and (c) 4.0–8.0 keV after NXB subtraction and correction for the vignetting effect. The coordinate refers to the J2000.0 epoch. The cyan contours in panel (a) indicate a radio continuum image at 1.4 GHz taken with the NRAO Very Large Array Sky Survey. The source and background spectra were extracted from the regions enclosed by the solid and dashed lines in panel (a), respectively. The source region was divided into 110 subregions as shown in panel (b). The regions enclosed by the green lines in panel (c) are the three representative subregions whose spectra are plotted in Figure 2. The white contours show the 0.5–4.0 keV X-ray image. The magenta arrow indicates the location of the PWN 1SAX J0617.1+2221. The cyan ellipses are regions excluded in the spectral analysis to remove bright point sources.

Table 2
Best-fit Model Parameters of the Background Spectrum

| Physical Component | XSPEC Model  | Parameter      | Value                  |
|--------------------|--------------|----------------|------------------------|
| GH                 | APEC (GHcold)| $kT_e$ (keV)   | 0.658 (fixed)          |
|                    |              | Norm$^a$       | 12.5 ± 1.2             |
| LHB                | APEC         | $kT_e$ (keV)   | 2.22 ± 0.02            |
|                    |              | Norm$^a$       | 66.8 ± 5.1             |
|                    | TBabs (absorption) | $N_{H}^{abs}$ | 45.1 $^{+7.2}_{-4.5}$   |
| CXB                | Power law    | $\Gamma$       | 1.40 (fixed)           |
|                    |              | Norm$^b$       | 12.1 $^{+1.3}_{-1.1}$   |
|                    |              | $\chi^2 (\nu)$ | 1.44 (224)            |

Notes.

a The emission measure integrated over the line of sight, i.e., \((1/4\pi D^2)\int n_e n_p dl\) in units of \(10^{-14} \text{ cm}^{-5} \text{ sr}^{-1}\).

b Units of photons s$^{-1}$ cm$^{-2}$ keV$^{-1}$ sr$^{-1}$ at 1 keV.

c The parameters $\chi^2$ and $\nu$ indicate a reduced chi-squared and a degree of freedom, respectively.

Figure 2. MOS (MOS1+MOS2) spectra extracted from the representative subregions 1 (black), 2 (green), and 3 (red) shown in Figure 1(c). The NXB and X-ray background are subtracted. For the purpose of display, the spectra of Regions 2 and 3 are scaled by factors of 0.2 and 4.0, respectively. The vertical solid and dashed lines denote the centroid energies of the He$\alpha$ lines and Ly$\alpha$ lines, respectively.
Based on spectroscopic analyses of the X-ray data, Matsumura et al. (2017) and Greco et al. (2018) claimed that thermal conduction and adiabatic expansion create the RP, respectively. Hirayama et al. (2019) and Yamauchi et al. (2021) proposed a new scenario completely different from above two scenarios. In this model, protons accelerated in SNRs enhance ionization of ions in plasmas, resulting in the overionization. All of the authors’ claims contradict each other and the physical origin of the RP in IC 443 is thus still been under active debate.

Here, we report the results from a spatially resolved analysis of XMM-Newton data of IC 443, aiming to reveal the physical origin of the RP. Throughout the paper, errors are quoted at 90% confidence levels in the tables and text. Error bars shown in figures correspond to 1σ confidence levels.

2. Observations and Data Reduction

IC 443 was observed several times from 2003–2013 with XMM-Newton. Table 1 summarizes the details of the observations. Once all observations are combined, the entire region of IC 443 is completely covered by the field of view of XMM-Newton. In what follows, we analyze data obtained with the European Photon Imaging Camera, which consists of two MOS cameras (Turner et al. 2001), and one pn CCD camera (Strüder et al. 2001).

We reduced the data with the Science Analysis System software version 16.0.0, following the recipe for the analysis...
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Table 3
Best-fit Model Parameters of the Spectra from the Representative Subregions

| Physical Component | XSPEC Model | Parameters | Region 1 | Region 2 | Region 3 (RP) | Region 3 (RP+ICIE) |
|--------------------|-------------|------------|----------|----------|---------------|-------------------|
|                    |             | \(N_\text{H} \left(10^{22} \text{ cm}^{-2}\right)\) | 1.02^{+0.03}_{-0.1} | 0.78 ± 0.03 | 0.78 ± 0.03 | 0.90 ± 0.01 |
| RP                 | VXRNEI      | \(kT_\text{e} \text{ (keV)}\) | 0.24 ± 0.02 | 0.23 ± 0.02 | 0.36 ± 0.02 | 0.53 ± 0.02 |
|                    |             | \(kT_{\text{int}} \text{ (keV)}\) | 5.0 (fixed) | 5.0 (fixed) | 5.0 (fixed) | 5.0 (fixed) |
|                    |             | \(Z_\text{O} \text{ (solar)}\) | 0.5 ± 0.1 | 0.4 ± 0.1 | 0.5±0.1 | <1.5 |
|                    |             | \(Z_{\text{Ne}} \text{ (solar)}\) | 1.1 ± 0.2 | 0.5 ± 0.1 | 1.0 ± 0.1 | 1.7 ± 0.2 |
|                    |             | \(Z_{\text{Mg}} \text{ (solar)}\) | 0.8 ± 0.1 | 0.5 ± 0.2 | 0.8 ± 0.1 | 1.2 ± 0.1 |
|                    |             | \(Z_{\text{Si}} \text{ (solar)}\) | 0.5 ± 0.1 | 1.0 ± 0.2 | 1.4 ± 0.2 | 2.0 ± 0.2 |
|                    |             | \(Z_{\text{Fe}} = Z_{\text{Ne}} = Z_{\text{S}} \text{ (solar)}\) | 1.2^{+0.1}_{-0.2} | 1.0 ± 0.1 | 1.1 ± 0.2 | 1.3 ± 0.2 |
|                    |             | \(\nu_{\text{e}} \left(10^{11} \text{ cm}^{-3} \text{ s}^{-1}\right)\) | 4.6 ± 0.2 | 12.7^{+1.1}_{-1.3} | 6.0 ± 0.2 | 5.5^{+0.3}_{-0.2} |
|                    |             | \(\text{Norm}^a\) | 0.30 ± 0.01 | 0.14 ± 0.02 | 0.14 ± 0.02 | 0.07 ± 0.01 |
| CIE                | APEC        | \(kT_\text{e} \text{ (keV)}\) | ... | ... | ... | 0.21^{+0.06}_{-0.07} |
|                    |             | \(Z_{\mu} \text{ (solar)}\) | ... | ... | ... | 1.0 (fixed) |
|                    |             | \(\text{Norm}^a\) | ... | ... | ... | 0.11 ± 0.02 |

\(\chi^2 \nu = 1.19 \left(342\right), 1.24 \left(201\right), 2.04 \left(335\right), 1.25 \left(333\right)\)

Notes.

1. The emission measure integrated over the line of sight, i.e., \(\int n_e n_H d\ell\) in units of \(10^{-14} \text{ cm}^{-5} \text{ sr}^{-1}\).

2. The parameters \(\chi^2\) and \(\nu\) indicate a reduced chi-squared and a degree of freedom, respectively.

Table 4
Average Charge \(\epsilon_{\text{RF}}\) and Charge Deviation \(\Delta C\) for Each Ion Species of RPs in the Representative Subregions

| Parameters | Region 1 | Region 2 | Region 3 |
|------------|----------|----------|----------|
| \(\epsilon_{\text{RF, O}}\) | 7.63 ± 0.05 | 7.3 ± 0.1 | 7.95^{+0.03}_{-0.06} |
| \(\epsilon_{\text{RF, Ne}}\) | 9.22 ± 0.04 | 8.4 ± 0.1 | 9.66 ± 0.01 |
| \(\epsilon_{\text{RF, Mg}}\) | 10.90^{+0.05}_{-0.03} | 10.13^{+0.06}_{-0.02} | 11.2^{+0.08}_{-0.06} |
| \(\epsilon_{\text{RF, Si}}\) | 12.53^{+0.05}_{-0.06} | 11.7 ± 0.1 | 12.8 ± 0.1 |
| \(\epsilon_{\text{RF, S}}\) | 13.8 ± 0.2 | 12.4^{+0.2}_{-0.2} | 14.5^{+0.3}_{-0.3} |
| \(\epsilon_{\text{RF, Fe}}\) | 15.7 ± 0.3 | 14.9^{+0.1}_{-0.5} | 17.6^{+0.1}_{-0.2} |
| \(\Delta C_{\text{O}}\) | 0.27^{+0.09}_{-0.07} | 0.09^{+0.03}_{-0.04} | (0.7^{+0.4}_{-0.1}) \times 10^{-5} |
| \(\Delta C_{\text{Ne}}\) | 1.04 ± 0.03 | 0.30^{+0.02}_{-0.06} | 0.11^{+0.02}_{-0.06} |
| \(\Delta C_{\text{Mg}}\) | 0.93^{+0.03}_{-0.03} | 0.16^{+0.03}_{-0.04} | 0.70^{+0.03}_{-0.04} |
| \(\Delta C_{\text{Si}}\) | 0.72^{+0.03}_{-0.05} | 0.06^{+0.01}_{-0.02} | 0.63^{+0.03}_{-0.04} |
| \(\Delta C_{\text{S}}\) | 1.5 ± 0.4 | 0.24^{+0.05}_{-0.10} | 0.8 ± 0.2 |
| \(\Delta C_{\text{Fe}}\) | 0.4 ± 0.1 | (2.8^{+3.3}_{-0.3}) \times 10^{-5} | 1.0^{+0.1}_{-0.2} |

procedures of extended sources.\(^6\) We used the calibration database version 3.12 released in 2019.\(^7\) We generated the redistribution matrix files and the ancillary response files.

3. Analysis and Results

3.1. Imaging Analysis

Figure 1 shows vignetting- and exposure-corrected images of IC 443. Overlaid in Figure 1(a) is the source region for spectral analysis. We perform spatially resolved spectroscopy using the same method as Okon et al. (2020). We applied the contour-binning algorithm (Sanders 2006) to the 0.5–4.0 keV image, and divided the source region into 110 subregions in

\(^6\) http://xmm.esac.esa.int/pub/xmm-esas/xmm-esas.pdf

\(^7\) https://xmmweb.esac.esa.int/doc/documents/CAL-TN-0018.pdf

Figure 5. Distribution of X-ray absorption column density (\(N_\text{H}\)). The cyan contours denote \(^{12}\)CO(J = 1–0) emissions in a velocity range of \(V_{\text{LSR}} = -18 \pm 2 \text{ kms}^{-1}\) as observed with NANTEN2 (Yoshiike 2017).
following spectral analysis, we manually excluded the identified point sources, whereas we modeled emissions from the PWN and PSR according to the work by Bocchino & Bykov (2003).

3.2. Background Estimation

For background estimation, we used spectra extracted from the off-source region in Figure 1(a). We subtracted the non-X-ray background (NXB) estimated with mos- back and pn- back from the spectra, and fitted them with a model consisting of the X-ray background model (Masui et al. 2009), and neutral Al and Si Kα lines of instrumental background, which are not included in the NXB spectra (Lumb et al. 2002). The X-ray background model consists of the cosmic X-ray background (CXB), the local hot bubble (LHB), and two thermal components for the Galactic halo (GHcold and GHhot). The photon index of the CXB component was fixed to 1.4 given by Kushino et al. (2002), whereas the normalization and the column density (NH_cXB) for the total Galactic absorption were allowed to vary. We used the Tuebingen–Boulder interstellar medium (ISM) absorption model (TBabs; Wilms et al. 2000) with the solar abundances (Wilms et al. 2000) for the interstellar absorption. Most of the parameters of the LHB, GHhot, and GHcold models were fixed to values given by Masui et al. (2009). The electron temperature kTe of GHhot, and the normalization of each component were left free. The normalization of the Al and Si Kα lines were allowed to vary because the line intensities are known to have location-to-location variations on the detector plane (Kuntz & Snowden 2008). The best-fit parameters are summarized in Table 2. In the subsequent spectral analyses, we used the best-fit model to account for the X-ray background emission.

3.3. Spectral Analysis

Previous X-ray studies (e.g., Matsumura et al. 2017; Greco et al. 2018) revealed the presence of RPs almost in the whole of IC 443. Figure 2 shows the spectra extracted from the representative subregions in Figure 1(c). One can clearly see resolved emission lines from highly ionized O, Ne, Mg, Si, S, and Ar ions, as well as their different Lyα/Heα ratios and...
distinct continuum shape between each spectrum. The spectral features indicate significant spatial variations of parameters of the RPs and of absorption column densities toward the remnant. To model the plasma emission, we used the non-equilibrium recombining collisional model, VVRNEI (Foster et al. 2017) model implemented in the XSPEC software version 12.10.1f (Arnaud 1996). The VVRNEI model can calculate the spectrum of thermal plasma in the overionized state after an abrupt decrease in the electron temperature. The described ionization state is time evolved with the recombination flux \( n_t \) after the cooling from \( kT_{\text{init}} \) to \( kT_e \) under the assumption that the plasma initially was in a CIE state. To take into account photoelectric absorption by the foreground gas, we applied the TBabs model. We allowed the column density \( N_{\text{HI}} \), the present electron temperature \( kT_e \), density-weighted recombination time, \( n_t \), and normalization of the VVRNEI component to vary. The initial plasma temperature \( kT_{\text{init}} \) is constrained to be \( \geq 5 \) keV, whose elements such as O–S are almost fully ionized. We fixed \( kT_{\text{init}} \) at 5 keV because other parameters such as \( N_{\text{HI}}, kT_e \), and \( n_t \) are hardly sensitive to the choice of \( kT_{\text{init}} \). We let the abundances of O, Ne, Mg, Si, S, Ar, Ca, Fe, and Ni vary, and tied Ar and Ca to S, and Ni to Fe. The abundances of the other elements were fixed to solar values. In spectral fittings of the subregions where the PWN 1SAX J0617.1+2221 or its pulsar is observed (Figure 1(c)), we applied a model that consists of the VVRNEI model and an additional power law to account for their emissions. The photon index \( \Gamma \) and the normalization of the power law were left free.

Figure 3 shows the results of the spectral fittings of Regions 1–3. The VVRNEI model describing an RP (with the additional power law) gives good fits to spectra from most of subregions including Regions 1 and 2 (Figures 3(a) and 4(b)). On the other hand, as represented by the example of Region 3 (Figure 3(c–i)), some fits left remarkable residuals at \( \sim 1.0 \) keV around Ne XI Ly\( \alpha \) line and \( \sim 2.0 \) keV around Si XV Ly\( \alpha \) line. These residuals suggest plasma parameters are different between the soft and hard bands. We followed the same modeling procedure as Matsumura et al. (2017), who reported the presence of a cooler ISM in addition to the hot RP components, and refitted the spectra from subregions with \( \chi^2 > 2.0 \) as indicated by the \( \chi^2 \) map in Figure 4(c–i). The spectra are well reproduced by the RP model with a CIE component Astrophysical Plasma Emission Code (APEC) for the ISM origin. In Figure 3(c–ii), we show the result of Region 3.

We also tried the non-equilibrium ionization (NEI) and plane-parallel shocked plasma (PShock) models, which are possible candidate models for the ISM component, instead of the APEC model to examine other model combinations well representing the overall spectra. The combination of the RP and either model successfully reproduces the spectra, but does not significantly improve the fitting statistics compared to that including the APEC model (for Region 3, VVRNEI+NEI: \( \chi^2 = 1.25 \) with \( \nu = 332 \); VVRNEI+PShock: \( \chi^2 = 1.24 \) with \( \nu = 332 \); VVRNEI+APCC: \( \chi^2 = 1.25 \) with \( \nu = 333 \)). The choice of the different ISM model does not change the RP parameters obtained beyond the 90% confidence level so that we used the model that consists of the VVRNEI and APEC. All subregions finally have \( \chi^2 < 2.0 \) as shown in the \( \chi^2 \) map (Figure 4(b)). The best-fit parameters of Regions 1–3 are summarized in Table 3.

To directly quantify the degree of overionization in RPs, we introduce the average charge of each ion species, \( \bar{C} \), and the deviation of the average charge from the CIE state with the same \( kT_e \), \( \Delta C \),

\[
\bar{C} = \sum_i c_i F_i
\]

\[
\Delta C = \overline{C_{\text{RP}}}(kT_e, n_t, kT_{\text{init}} = 5 \text{ keV}) - \overline{C_{\text{CIE}}}(kT_e),
\]

where \( c_i \) and \( F_i \) are the charge number and fraction of \( i \)-times ion, respectively. We computed \( F_i \) by using PyAtomDB.\(^8\) \( \bar{C} \) and \( \Delta C \) of Regions 1–3 are listed in Table 4.

### 4. Discussion

#### 4.1. Foreground Gas Distribution

The foreground gas absorption \( N_{\text{HI}} \) serves to probe the spatial distribution of the gas in front of the remnant. Figure 5 shows the \( N_{\text{HI}} \) values of each subregion. We overlay the \( ^{12}\text{CO}(J = 1−0) \) emission observed with NANTEN2 (Yoshiike 2017). The \( N_{\text{HI}} \) map reveals higher values in subregions where the \( ^{12}\text{CO} \) emission is detected. The spatial match was pointed out first by Matsumura et al. (2017) and supports an interpretation that most of the gas traced by the CO line is present in front of IC 443. Does the amount of gas expected by the spatial variation of \( N_{\text{HI}} \) account for the CO data? We roughly estimated the column density of the foreground gas to be \( \sim 0.6 \times 10^{22} \) cm\(^{-2} \) with the difference in the \( N_{\text{HI}} \) values of the \( ^{12}\text{CO} \) line observed and not observed subregions. Yoshiike (2017) estimate the column density \( N_{\text{H}, \text{CO}} \approx 0.6 \times 10^{22} \) cm\(^{-2} \) with the NANTEN2 data. Given that the amount of the atomic gas traced by H I emissions is less than that of the gas traced by the CO line (Yoshiike 2017), our measurement is consistent with the radio one.

#### 4.2. Physical Origin of RPs

We first focus on the thermal conduction and rarefaction scenarios, which are potentially responsible for the over-ionization in IC 443. Spatial comparisons between \( kT_e, n_t \), and the shocked clouds give crucial information for disentangling the two scenarios (Yamaguchi et al. 2018; Okon et al. 2020).

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\(^8\) https://atomdb.readthedocs.io
We map the $kT_e$ and $n_e$ derived from the subregions (Figure 6) and plot them (Figure 7). The $^{12}$CO($J = 2–1$)-to-$^{13}$CO($J = 1–0$) line ratio and H$_2$ 1–0 S(1) line contours are superposed on the maps to clarify the locations of shocked clouds. Based on these maps, we color data points from on-cloud subregions, which overlap with either of the $^{12}$CO or H$_2$ emission, in red in the plot. We find decreased $kT_e$ and $n_e$ of RPs toward the on-cloud subregions.

The physical implication of the gradients of $kT_e$ and $n_e$ in RPs can be understood by investigation of the charge fraction for each ion. In Figures 8 and 9, the average charge $C_{RP}$ and the charge deviation $\Delta C$ are shown on the same $kT_e$–$n_e$ plot as that in Figure 7. We also present the maps of $\Delta C$. RPs with lower $kT_e$ and $n_e$ of RPs toward the on-cloud subregions.

Figure 8. Average charge $C_{RP}$ and charge deviation $\Delta C$ for O–Mg ions in panels (a-i)–(c-i) and (a-ii)–(c-ii), respectively, shown on color scales. We overlay the same plot as that in Figure 7 on each map. In panels (a-iii)–(c-iii), maps of $\Delta C$ are computed with best-fit values. The cyan contours denote the same radio H$_2$ image as that in Figure 6.

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It is interesting to point out that our result for IC 443 is similar to that on W44, whose RP is also ascribed to thermal conduction (Okon et al. 2020). Regions with lower $kT_e$ and $n_e$ in W44 completely coincide with the locations where a spatially extended broad $^{12}$CO line, the so-called SEMBE, is observed. Although the nature of SEMBE is not clear yet, the emission is considered to be from small clumps (Sashida et al. 2013) disturbed after the shock propagation (Seta et al. 2004; Sashida et al. 2013). Okon et al. (2020) claimed that hot plasma is efficiently cooled by evaporation of the clumps embedded in the plasma via thermal conduction. The same mechanism may account for the $kT_e$ and $n_e$ trends in IC 443. A deep and high angular resolution CO mapping would help to search for the spatially extended broad-line structures. Comparison between the degree of overionization of RPs and the properties of the shocked gas can provide a step forward in the study of the cooling mechanism via thermal conduction.

Hirayama et al. (2019) and Yamauchi et al. (2021) proposed a new scenario where the overionization in SNRs is caused by...
bombardment of accelerated protons. Given ionization cross sections, sub-relativistic protons may more efficiently ionize ions than thermal electrons in the plasma. We test the possibility from the viewpoint of the energetics of particle acceleration. Figure 10 shows the Si ion population in the RP with typical parameters obtained, $kT_e = 0.3$ keV, and $n_{e,t} = 6.0 \times 10^{11}$ cm$^{-3}$ s, and that in a CIE plasma with the same $kT_e$. To explain the strong H-like Si RRC in the IC 443 spectra, which is solid evidence for the RPs (e.g., Yamaguchi et al. 2009), some of the abundant He-like Si ions in the CIE plasma must be ionized to the H-like and subsequently to fully ionized states.

We now estimate the required energy density of sub-relativistic protons under the condition that the ionization of He-like to H-like Si ions by the proton bombardment proceeds faster than the relaxation toward a CIE state. The ionization rate $\xi$ can be described as

$$\xi = \int \sigma_i v \frac{dn_p}{dE} dE,$$

where $\sigma_i$ is the K-shell ionization cross section for He-like Si ions. Assuming the proton spectrum $dn_p/dE \propto E^{-2}$ expected in diffusive shock acceleration at a strong shock and $\sigma_i$ by McGuire & Richard (1973), $\xi$ is estimated as

$$\xi \sim 3.3 \times \left( \frac{n_p}{1.0 \text{ cm}^{-3}} \right) \times 10^{-12} \text{ s}^{-1},$$

where $n_p$ is the proton density integrated in the energy range from 0.2–20 MeV, corresponding to the integral ranges of Equation (3). Smith & Hughes (2010) gave the characteristic
timescale toward CIE as
\[ \Lambda \sim 3 \times \left( \frac{n_e}{1.0 \text{ cm}^{-3}} \right)^{-1} \times 10^{11} \text{ s}. \]  

(5)

To meet the condition, \( \xi \) must be larger than \( \Lambda^{-1} \). If \( n_e \) is 1.0 cm\(^{-3}\), \( n_p \) is estimated to be \( \gtrsim 1.0 \text{ cm}^{-3} \). The energy density \( \epsilon_p \) and total energy \( E_p \) can be described as
\[ \epsilon_p = \int E \frac{dhp}{dE} dE \sim 0.9 \times \left( \frac{n_p}{1.0 \text{ cm}^{-3}} \right) \text{MeV cm}^{-3}, \]  

(6)
\[ E_p = \epsilon_p \cdot V \cdot f, \]  

(7)

where \( V \) and \( f \) are the volume of the whole IC 443 and the filling factor, respectively. Assuming the volume is a sphere with a radius of \( \sim 10 \text{ pc} \), \( E_p \) is estimated to be \( \sim 1.8 \cdot f \cdot (n_p/1.0 \text{ cm}^{-3}) \cdot 10^{53} \text{ erg} \). The proton energy certainly exceeds the typical kinetic energy \( \sim 10^{51} \text{ erg} \) in supernova explosions even if we consider the uncertainty of \( f \). Our estimation thus indicates that it is difficult to explain the observed RPs in IC 443 only by the proton ionization claimed by Hirayama et al. (2019) and Yamauchi et al. (2021) and the contribution is negligible.

5. Conclusions

We have performed spatially resolved spectroscopy of the X-ray emission of IC 443 with XMM-Newton, aiming to clarify the physical origin of the overionization. All spectra extracted from each region are well fitted with an RP model or the RP model with an additional CIE model of shocked ISM origin. The X-ray absorption column density is higher in the region where the shock is interacting with ambient clouds. The obtained electron temperature \( kT_e \) and the recombining degree \( n_{\text{re}} \) of RPs range from 0.15–0.65 keV and from 4.0 \times 10^{11} \text{ cm}^{-3} \) to \( 14 \times 10^{11} \text{ cm}^{-3} \), respectively. We have discovered that RPs in the region where the shock is interacting with ambient clouds tend to have lower \( kT_e \) and smaller \( n_{\text{re}} \). Based on the computation of the charge fraction for ions, these tendencies indicate that RPs in the region are more cooled and more strongly overionized, and can be naturally explained by a rapid cooling via thermal conduction. Given the similar result for W44 reported by Okon et al. (2020), evaporation of clumpy gas embedded in the hot plasma may cause the rapid cooling. We have also discussed the possibility that ionization of protons accelerated in IC 443 is responsible for the overionization. Based on the energetics of particle acceleration, we conclude that proton bombardment is difficult to explain the observed properties of the RPs.

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