Construction of a semi-phenomenological model for the IC 443 plasma with strong radiative recombination continua

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Abstract

The X-ray spectrum of the Galactic supernova remnant (SNR) IC 443 exhibits extremely strong radiative recombination continua (RRC). In order to study the spectrum quantitatively, we construct a semi-phenomenological model with bremsstrahlung, emission lines, and RRC. We fit the spectrum with this model and obtain reasonable agreement. By using this new model fitting, electron temperatures are obtained in three independent ways: the line flux ratios of Kβ–Kδ to Kα, the bremsstrahlung shape, and the RRC width. On the other hand, the ionization temperature is obtained by the flux ratio of H-like to He-like Kα lines. The fact that ionization temperature (1.1–1.4 keV) is higher than the electron temperature (0.4–1.0 keV) indicates the plasma is in an overionized state, which is very unusual for SNRs.

Key words: ISM: individual (IC 443) — supernova remnants — radiation mechanisms: thermal

1. Introduction

IC 443 (G189.1+3.0) is one of the mixed-morphology supernova remnants. Kawasaki et al. (2002) claimed the presence of "overionized" plasma using *ASCA* data. They measured intensity ratios of the H-like Kα (hereafter Lyα) to He-like Kα (Heα) lines of S to obtain the ionization temperature (kT_Z). They found that kT_Z ($\sim$1.5 keV) is significantly higher than the electron temperature (kT_e) determined from the bremsstrahlung shape ($\sim$1.0 keV).

Yamaguchi et al. (2009) have recently discovered the strong radiative recombination continua (RRC: X-ray emissions due to the free-bound transition of electrons) of Si and S from IC 443. They fitted the spectrum with the thin-thermal plasma code (APEC: Smith et al. 2001) in the collisional ionization equilibrium (CIE) state, additional Gaussians to reproduce Lyα intensities, and the RRC. In this paper, we introduce the new fitting model to study the spectrum quantitatively with the X-ray Imaging Spectrometers (XIS) onboard the *Suzaku* satellite. The details of the observation and data reduction are found in Yamaguchi et al. (2009).

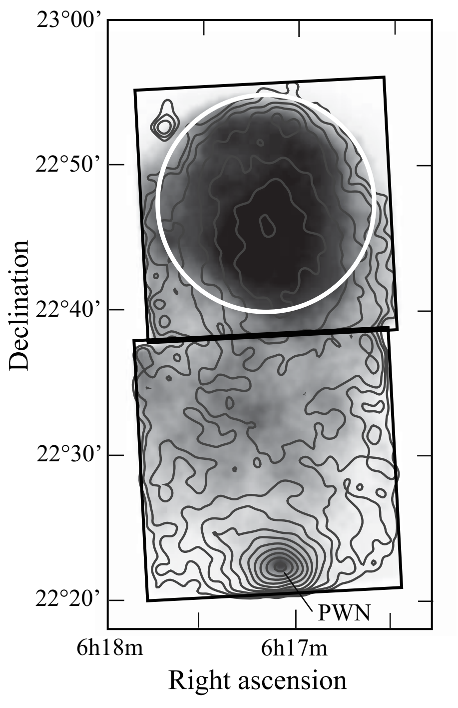

Fig. 1. Vignetting-corrected and NXB subtracted XIS image of IC 443 shown on logarithmic intensity scale (grey scale: 0.7–3 keV, contours: 3–5.5 keV). Black squares and a white circle are the XIS field of views and a region used in our spectral analysis, respectively. The coordinates (R.A. and Dec.) refer to epoch J2000.0.

2. Analysis

Figure 1 shows an XIS image of the observed fields. We extract the spectra from a circular region with radius of 7.5 arcmin. The non–X-ray background (NXB) spectra from the same region on the detector are constructed us-

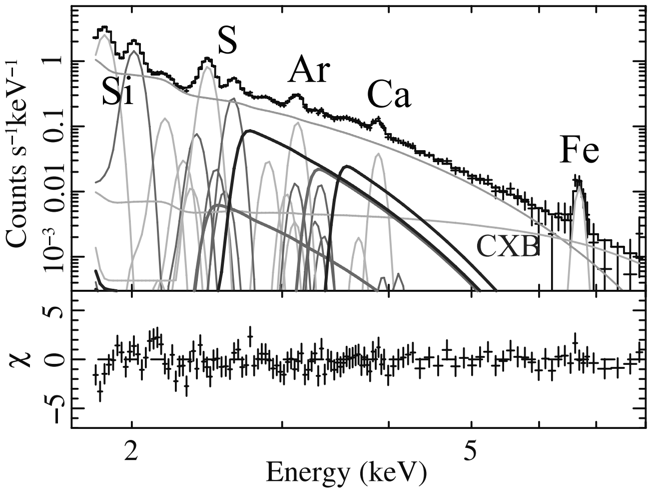

Fig. 2. 1.8–8 keV XIS-FI spectra fitted with a semi-phenomenological model consisting of bremsstrahlung, Gaussians, and RRC.

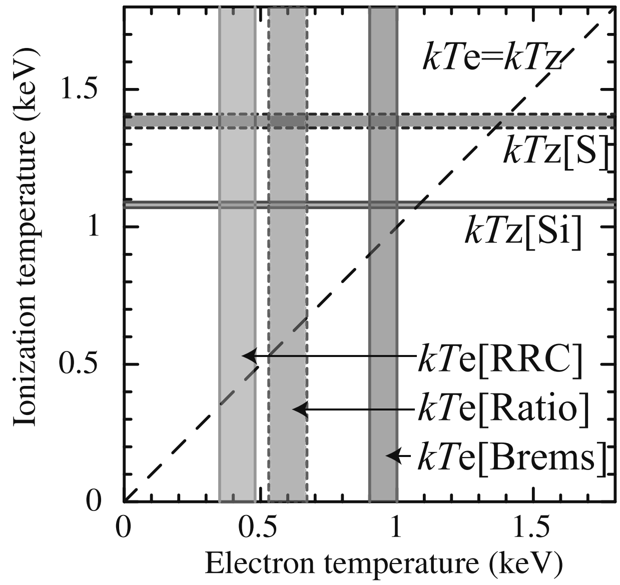

Fig. 3. Temperatures derived from the spectral fitting. $kT_{\rm e}$[Ratio], $kT_{\rm e}$[Brems], and $kT_{\rm e}$[RRC] are electron temperatures derived from the Kβ–Kδ to Kα flux ratios, the bremsstrahlung shape, and the RRC width, respectively. $kT_{\rm Z}$[Si] and $kT_{\rm Z}$[S] are ionization temperatures derived from the Lyα/Heα ratio of Si, and that of S, Ar, and Ca, respectively.

ing xisnxbgen software, and subtracted from the source spectra. The resultant spectra exhibit the K-shell emission lines from He- and/or H-like ions of O, Ne, Mg, Si, S, Ar, and Ca, as well as L-shell emission blends of Fe (Yamaguchi et al. 2009). Furthermore, we resolve the Fe-Kα line for the first time (see Figure 2). Kβ lines of Ne, Mg, Si, and S are also resolved. The firm detection of these lines enables us to obtain precise electron and ionization temperatures.

We here focus on the 1.8–8 keV spectral fitting. We fix the interstellar extinction to $N_{\rm H} = 7{\times}10^{21}{\rm cm}^{-2}$, following Kawasaki et al. (2002). The cosmic X-ray background which is still included in the NXB-subtracted spectra is modeled following Kushino et al. (2002).

2.1. Construction of a semi-phenomenological model

We construct the model with bremsstrahlung, emission lines, and RRC. We use Gaussians to represent the emission lines, and take account of Kα–Kδ emission lines for Si and S, Kα–Kβ lines for Ar, Ca, and Fe. For all Gaussians, we fix center energies to that of the APEC code, and the widths to zero. Using the APEC code, we restrict the individual flux ratios of Kβ–Kδ to Kα for He-like and H-like atoms as a function of $kT_{\rm e}$, which is common among all the elements. We also restrict Lyα/Heα ratio as a function of $kT_{\rm Z}$. We link $kT_{\rm Z}$ of S, Ar, and Ca, because Lyα intensities of Ar and Ca are not strong enough.

For RRC structures, we use the REDGE model which is built into XSPEC. We consider RRC from fully-ionized and H-like atoms of Si and S. We fix edge energies to the K-shell binding potentials and link all the RRC widths. All the normalizations of the RRC components are free parameters.

2.2. Fitting results

Figure 2 shows the fitting result of the phenomenological model with an acceptable χ^2/dof of 306/280. If we exclude the RRC, the fit leaves large residuals around 2.7 and 3.5 keV, and rejected with large χ^2/dof of 845/285.

From the fitting results, we obtain $kT_{\rm e}$ in three independent ways: 1) the line flux ratios of Kβ–Kδ to Kα, 2) the bremsstrahlung shape, and 3) the RRC width. On the other hand, $kT_{\rm Z}$ is obtained by the Lyα/Heα flux ratio. The results are shown in Figure 3. All $kT_{\rm Z}$ are significantly higher than $kT_{\rm e}$, indicating the existence of overionized plasma in IC 443. Note that these temperatures are derived based on the APEC code in the CIE state. In a precise sense, we should use an overionization code such as Masai (1994). Detailed treatments and discussions are found in Yamaguchi et al. (2009).

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