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Suzaku view of supernova remnants

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Abstract. We present the spectral studies of thermal emissions from supernova remnants (SNRs) with the latest Japanese X-ray astronomy satellite Suzaku. In the X-ray spectrum from the southeast region of SN 1006, we robustly detected the K-shell emission from Fe, for the first time. Fe was found to be less ionized than the other lighter elements, such as Si and S. This fact strongly suggests that Fe has been heated by the reverse shock more recently than the other elements, consistent with a picture where the ejecta are stratified by composition with Fe in the interior. From the several other Type Ia SNRs, Tycho, Kepler, and N103B, Suzaku successfully detected emission lines of low-abundant elements, Cr, Mn, and/or Ni. A number ratio of Mn/Cr in Type Ia SNRs would especially be a good probe for an initial metallicity of the progenitor, because the product of Mn is sensitive to the neutron excess in the white dwarf. We finally report on the recent results concerning the middle-aged SNRs, IC 443 and W49B. We discovered strong free-bound emission from these SNRs, the firm evidences of peculiar recombining (overionized) plasma.

Key words. ISM: Supernova Remnants – X-Rays: Spectra

1. Introduction

Most of the heavy elements in the present universe had been synthesized in stars, and were ejected to interstellar space by supernova (SN) explosions. Therefore, we are motivated to study the nucleosynthesis (nuclear fusion) and explosion mechanisms of SNe, in order to understand chemical evolution of the universe.

Although many SN explosions have been extensively studied in optical wavelength, the light from the inner region cannot be observed directly due to quite high density of SN ejecta immediately after the explosion. We can, therefore, obtain only the information of the synthesized elements laid on the surface layer of SNe. On the other hand, the remnants of SNe, supernova remnants (SNRs), at the age of a few hundreds or thousands years are generally bright in X-ray band and dominated by the thermal emission from ejecta. Moreover, the hot plasma is optically thin, and hence all the elements in SNRs can be directly observed at the same time. This is the most remarkable advantage of the X-ray observation on SNRs.

Suzaku (Mitsuda et al. 2007) is the fifth Japanese X-ray astronomy satellites, developed by a Japanese–US collaboration and launched on Jury 2005. The observatory is equipped with CCD detectors, X-ray Imaging Spectrometers (XIS: Koyama et al. 2007) lo-

Send offprint requests to: H. Yamaguchi cated at the focal plane of X-Ray Telescopes (XRT: Serlemitsos et al. 2007). The XIS has imaging capability in the energy range of 0.2–10 keV, with large effective area, high energy resolution, and low and stable background level. Therefore, Suzaku is optimum for detection and diagnostics of emission lines from thin-thermal plasma. In this paper, we report on the representative results on the thermal X-ray emissions from SNRs obtained with Suzaku.

2. Fe-K emission from SN 1006

SN 1006 is believed to be one of the Galactic Type Ia SNRs similar to Kepler and Tycho SNRs. The current SN models predict that the Fe production in Type Ia SNe is far larger than that of core-collapse SNe (e.g., Nomoto et al. 1984; Iwamoto et al. 1999). Therefore, measuring the Fe abundance is one of the essential clues to classify the SN type of any specific remnant. The emission lines from ionized Fe had been detected in the X-ray spectra of Kepler (Kinugasa & Tsunemi 1999) and Tycho SNR (Hwang et al. 1998). In the case of SN 1006, ultraviolet observations suggested the existence of cold Fe by the detection of blue and red-shifted Fe II absorption lines in the spectra of the background stars (e.g., Winkler et al. 2005). However, any direct information of Fe has never been obtained.

The entire region of SN 1006 was observed by Suzaku. Since the northeast and southwest regions are known to be dominated by strong non-thermal (synchrotron) emissions from accelerated electrons (Koyama et al. 1995), we analyzed the X-ray spectra from the southeast quadrant in order to investigate its thermal spectral properties. The background-subtracted spectra are shown in Fig. 1. We detected clear K-shell (Kα) lines from Ar, Ca, and Fe, for the first time. Moreover, we found the line center energy of the Fe-Kα to be ~ 6.43 keV. This centroid constrains the Fe ionization state to be approximately Ne-like.

We found the broadband spectra were well represented with a model consisting of three optically thin thermal non-equilibrium ionization plasmas and a non-thermal emission. Details of the analysis procedure is found in Yamaguchi et al. (2008). Two of the thermal components are highly overabundant in heavy elements, and hence are likely due to ejecta. These components have different ionization parameters, $n_e t \sim 1.4 \times 10^{10}$ cm^{-3} s (Ejecta 1) and $n_e t \sim 7.7 \times 10^{8}$ cm^{-3} s (Ejecta 2). On the other hand, the third thermal component has solar elemental abundances, and hence we associate it with emission from the interstellar medium (ISM). The electron temperature ($kT_e \sim 0.5$ keV) of the ISM component is lower than that expected from the shock velocity of ~ 2900 km s^{-1} (Ghavaian et al. 2002), suggesting that temperatures of ion and electron are far from equilibrium.

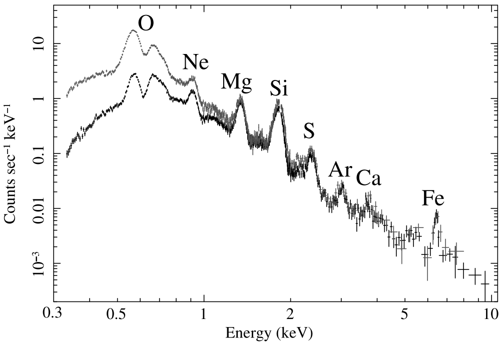

Fig. 1. Background-subtracted XIS spectra from the southeast quadrant of SN 1006. The black and gray data points represent the spectra of Front-Illuminated (FI) and Back-Illuminated (BI) CCDs, respectively.

Since Ejecta 1 has a larger ionization parameter than the other ejecta component, we suggest that this plasma was heated by reverse shock in the early stage of remnant evolution. On the other hand, Ejecta 2 has an extremely low ionization parameter, and hence should have been heated much more recently. We compare our best-fit relative abundances with the predicted nucleosynthesis yield of the widely-used W7 SN Ia model (Nomoto et al. 1984). For Ejecta 1, although the abundances of C, Ne, Mg, Si, and S relative to O are broadly consistent with the W7 model, Ca and Fe fall far below their predicted values, as shown in Fig. 2a. In the case of Ejecta 2, on the other hand, the heavy elements, albeit with large errors, are broadly consistent with

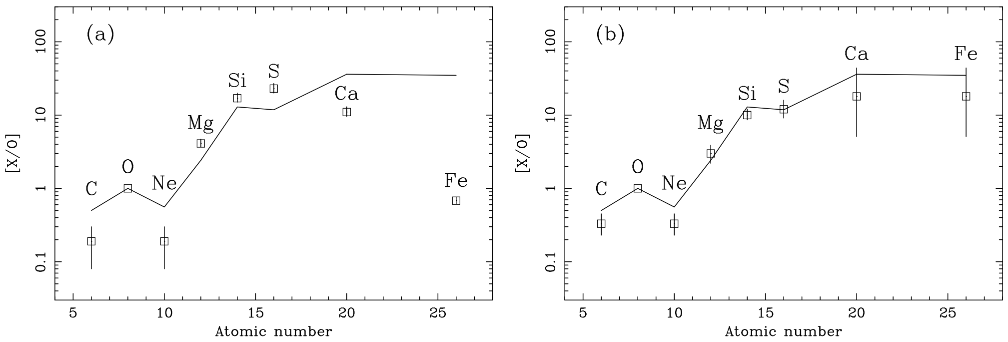

Fig. 2. Metal abundances as a function of atomic number derived from the spectral fitting. The data points of (a) and (b) represent those of Ejecta 1 and Ejecta 2, respectively. The solid lines show the abundances relative to oxygen calculated in the W7 model for a Type Ia supernova by Nomoto et al. (1984).

the abundance pattern from the W7 model, as shown in Fig. 2b. These results, along with the difference in the ionization timescale between the components just mentioned, are consistent with a layed composition of the ejecta with the higher-Z elements more concentrated toward the center of SN 1006.

3. Low-abundant elements in Tycho, Kepler, and N103B

Tycho SNR, recorded by Tycho Brahe in 1572, is classified as a normal Type Ia SNR based on its light-echo spectrum (Krause et al. 2008). The X-ray emission from Tycho SNR is known to be dominated by shock ejecta. Hwang & Gotthelf (1997) found many emission-line features of Mg, Si, S, Ar, Ca, and Fe, using ASCA data. All narrow band images of these emission lines showed the shell-like morphologies, but they are clearly distinct from each other. In particular, the radial profile of the Fe-K line peaks at a smaller radius than the those of the other emission lines and hard continuum emission. Furthermore, Hwang et al. (1998) showed that the ionization age of Fe is much lower than those of the other lighter elements. These facts suggest an incomplete mixing of the Si and Fe layers.

Details of the Suzaku observation and analysis of Tycho SNR are summarized in Tamagawa et al. (2009). The atomic emission lines below 4 keV have been well studied by previous missions, ASCA (Hwang & Gotthelf 1997), Chandra (Warren et al. 2005; Badenes et al. 2006), and XMM-Newton (Decourchelle et al. 2001). Thus, we here focus on the spectra above 4 keV, where Suzaku has a larger effective area and a lower background level than those of the other missions. Fig. 3 shows the XIS spectrum of entire Tycho SNR in the 4.0–8.5 keV energy range. In addition to intense Fe-Kα line, emissions from Cr and Mn are clearly detected, for the first time. The presence of Mn, which has an odd atomic number, is particularly important for constraining the property of Type Ia progenitor, as described by Badens et al. (2008).

During stellar evolution, the C, N, and O that act as catalysts for the CNO cycle pile up into ^{14}N. This is converted to neutron-rich element ^{22}Ne in the following hydrostatic He burning phase. Thus, the large neutron excess of the white dwarf is expected if the initial metallicity of the progenitor is high (e.g., Timmes et al. 2003). The products of Type Ia SN with an odd mass number, such as Mn, would be sensitive to the neutron excess, while that of even mass number, such as Cr, is insensitive. Therefore, the number ratio of Mn/Cr in Type Ia SN ejecta is suggested as a good tracer for the initial metallicity of the progenitor. Badens et al. (2008) argued that the progenitor of Tycho SNR had a supersolar metallicity, based on the observed Mn/Cr ratio.

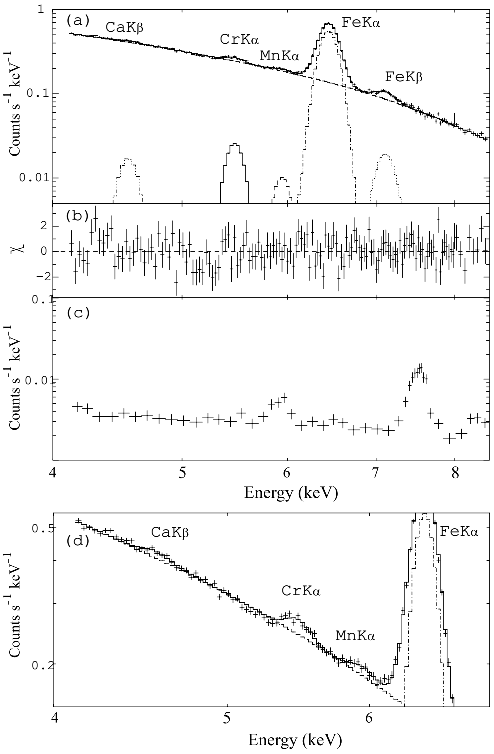

Fig. 3. (a) XIS-FI spectrum of Tycho's SNR above 4.0 keV. (b) Residuals of the fitting. (c) Background spectrum. (d) Magnified spectrum in energies of 4.0–6.5 keV.

Suzaku had also detected low-abundant elements from the other Type Ia SNRs. In the spectrum of Kepler SNR, not only Cr and Mn but also Ni emission lines have been detected significantly (Tamagawa et al., in preparation). The Mn/Cr ratio was found to be larger than that of Tycho SNR, implying a larger metallicity of the Kepler's progenitor. From N103B, one of the SNRs in the Large Magellanic Cloud, the emission line of Cr has been firmly detected as shown in Fig. 4. The center energy of the Cr-Kα ($\sim$ 5.54 keV) corresponds to the ionization state of B-like. The line-like feature of Mn can also be seen, albeit marginally. Note that this is the first detection of these elements from an extra-Galactic SNR. Details of the analysis will be found in a future paper (Yamaguchi et al., in preparation).

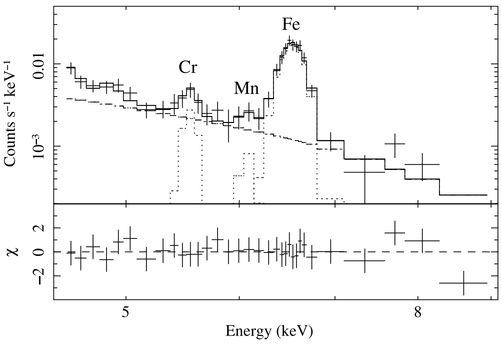

Fig. 4. XIS-FI spectrum of N103B in 4.5–9.0 keV.

4. Overionized plasma in IC 443 and W49B

In this section, we present the recent Suzaku discoveries of strong radiative recombination continuum (RRC) emissions from Galactic middle-aged SNRs, IC443 and W49B. As discussed below, these are the obvious evidences of peculiar plasma in "overionization" state.

IC 443 (jellyfish nebula) is located near the Gem OB1 association and a dense giant molecular cloud (Cornett et al. 1977). These facts strongly suggest that the remnant originated from a collapse of a massive progenitor. Troja et al. (2008) derived the age of ~4000 yr from the morphologies of the shocked ejecta and ISM revealed by XMM-Newton. 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 ($kT_z > kT_e$). However, Troja et al. (2008) claimed that the overionization is only marginal.

To investigate whether the overionized plasma is really present or not, we observed IC 443 with Suzaku. Fig. 5 shows the XIS spectrum in 1.75–6.0 keV from the representative region of the SNR. Details of the data reduction and analysis are found in Yamaguchi et al. (2009). In Fig. 5 (a), the spectrum is fitted with a model of an ionization equilibrium plasma plus narrow Gaussians to represent anomalously-strong Lyman emissions. We

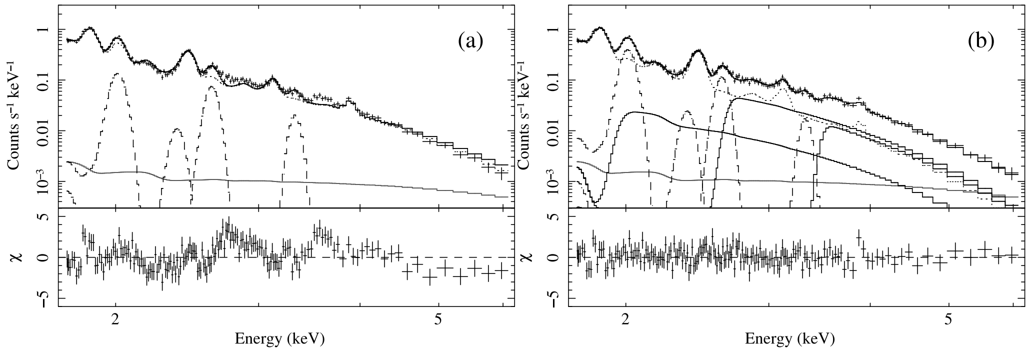

Fig. 5. (a) XIS-FI spectrum of IC 443 in 1.75–6.0 keV fitted with an ionization equilibrium plasma and additional Lyman lines. The lower panel shows the residual from the best-fit model. The hump-like features are clearly found around the energies of ~2.7 keV and ~3.5 keV. (b) Same spectrum as (a), but for a fit with RRC components of H-like Mg, Si, and S (black solid lines). The residuals seen in (a) are disappeared.

can see apparent hump-like residuals around ~2.7 keV and ~3.5 keV. 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 RRC spectrum is approximated as

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

Adding RRC for H-like Mg, Si, and S, the fit was dramatically improved as shown in Fig. 5 (b). The electron temperature was determined to be $kT_e \sim 0.6$ keV.

We compared the obtained flux ratios of H-like RRC to He-like Kα line ($F_{\rm RRC}/F_{\rm He\alpha}$) with the modeled emissivity ratios by the plasma radiation code of Masai (1994) for the electron temperature of 0.6 keV. Then, we found that the large ratios of $F_{\rm RRC}/F_{\rm He\alpha}$ are significantly above those in the ionization equilibrium case, but can be reproduced in the overionization case (see Yamaguchi et al. 2009, in detail). The ionization temperatures (kT_z) of Si and S are determined to be $\sim$ 1.0 keV and $\sim$ 1.2 keV, respectively. This is, therefore, the firm evidence of the overionized (recombining) plasma.

As the origin of the overionization, we propose the rapid and drastic cooling due to a rarefaction process 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. Indeed, 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).

Similar RRC spectrum has been observed in another SNR W49B. This SNR is also associated with star forming region (W49A; Brogan & Troland 2001). Keohane et al. (2007) showed an X-ray image of Chandra with a barrel-shaped structure, and interpreted this as an evidence that the progenitor had exploded inside a wind-blown bubble in a dense molecular cloud.

Fig. 6 shows the XIS spectrum above 5.0 keV extracted from the entire SNR. The spectrum exhibits an unusual saw-edged hump structure above ~8.8 keV. We found that this hump cannot be explained by any combination of high temperature plasmas in ionization equilibrium, but is caused by the strong RRC of He-like Fe (I_z = 8830 eV). The electron

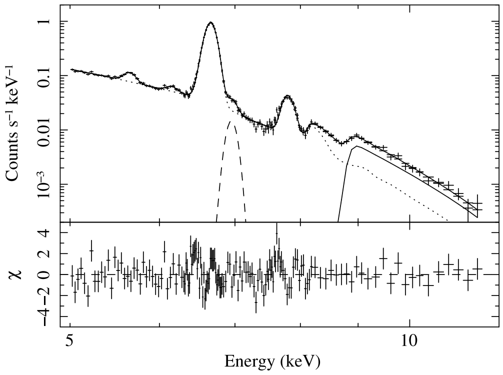

Fig. 6. XIS-FI spectrum of W49B in 5.0–10 keV. The solid line represents the RRC of He-like Fe.

temperature derived from the bremsstrahlung continuum shape and the slope of the RRC is ∼1.5 keV, while the ionization temperature derived from the observed intensity ratios between the RRC and Kα lines of Fe is ∼2.7 keV. These results indicate that the plasma is in a highly-overionized state, like IC 443. Thus, similar mechanism to form overionization, i.e., the rarefaction scenario, can be considered. Details of the analysis and discussions are presented in Ozawa et al. (2009).

5. Conclusions

We reported the recent Suzaku results on several SNRs. Since the CCD detectors (XIS) on board Suzaku have high sensitivity and good energy resolution, they are optimum for detection of weak emission structure, such as emission lines of low-ionized or low-abundant elements and radiative recombination continua. These detections are very useful to constrain the properties of the progenitors and/or mechanisms of supernova explosions.

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