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Spectroscopic studies of iron emissions from supernova remnants with Suzaku

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Abstract. We present X-ray spectroscopy of iron (Fe) emission from supernova remnants (SNRs) with Suzaku. Although young SNRs retain crucial information about their explosion and nucleosynthesis mechanisms, interactions with the surrounding material can conceal these data. Therefore, it is not unusual that even the basic progenitor type (i.e., Ia or core-collapse) of a remnant remains controversial. Our proposed method, solely using the Fe K-shell X-ray spectrum, successfully discriminates the progenitors of young ejecta-dominated SNRs. We find that the Fe ejecta in Type Ia SNRs are commonly less ionized than those in core-collapse SNRs. It is found, moreover, that luminosity and centroid of the Fe-K emission are well correlated among each group of Type Ia or core-collapse remnants, and that the more luminous remnants tend to be more highly ionized. These results may reflect the pre-explosion density of the remnants as well as the amount of the synthesized Fe. We also mention historical development of the X-ray studies of SNRs.

Key words. ISM: abundances – ISM– Supernova remnants

1. Introduction

Most of heavy elements in the present universe had been synthesized in stars and ejected to interstellar space by supernova (SN) explosions. We are therefore motivated to study the nucleosynthesis and explosion mechanisms of SNe to understand chemical evolution of the universe. Through a SN explosion, huge energy (typically of the order of 10^{51} erg) is released in form of the kinetic energy of the ejecta. As the supernova remnant (SNR) expands supersonically, shock waves are formed to compress and heat the ejecta and ambient matter. The shocked matters are hot enough to emit X-rays, hence an X-ray observation of SNRs offers useful information of the mechanism of SN explosion and nucleosynthesis.

2. Historical development of x-ray studies of SNRs

To date, spectroscopic and imaging capabilities of X-ray astronomy satellites have been complementary to our understanding of the nature of SNe/SNRs. Einstein and Tenma resolved emissions from different elements and revealed, for the first time, that an X-ray spectrum of SNRs is reasonably characterized by an optically-thin thermal plasma which is not in the ionization equilibrium (Vedder et al. 1986; Tsunemi et al. 1986). The ROSAT satellite performed the all sky survey with high spatial resolution of $\sim 25''$. This enabled us to

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investigate detailed structure of large SNRs, such as Cygnus Loop and Vela SNR ($\sim 2^\circ$ and $\sim 8^\circ$ in diameter, respectively). From the latter, several fragmental (bow-shock) features were discovered at the outside of the primary forward shock shell (Aschenbach et al. 1995), suggesting inhomogeneous explosion of the core-collapse (CC) SN. Also, the ROSAT all-sky data revealed a number of new SNRs in our Galaxy, e.g., RX J0852.0–4622 (G266.2–1.2: Aschenbach 1998) and RX J1713.7–3946 (G347.3–0.5: Koyama et al. 1997; Slane et al. 1999).

The biggest breakthrough of X-ray imaging spectroscopy was provided by ASCA in 1990's. This satellite was equipped with X-ray charge coupled device (CCD) detectors, for the first time, achieving unprecedented energy resolution. This made abundance measurements on SNRs much easier than before. One of the fragments in the Vela SNR was found to exhibit a strong line emission from Si with relatively weak signatures of the other elements (Tsunemi et al. 1999), suggesting its origin of the SN ejecta. Given that Si is synthesized in a deep layer of a massive progenitor, this result implies the violent, highly asymmetric SN explosion. Hughes et al. (1995) compared spectra of several SNRs in the Large Magellanic Cloud (LMC) with those expected from nucleosynthesis yields of Type Ia and core-collapse SNe. Their origins were then discriminated, although a controversial interpretation remained (see Section 3). Another remarkable feature of ASCA was the imaging capability in the wide energy range (0.5–10 keV). Owing to this capability, we became able to perform an imaging spectroscopy in the Fe-K emission band. The observation of the Tycho's SNR revealed that the Fe ejecta is located interior compared to the other lighter elements (e.g., Si, S, Ca) (Hwang & Gotthelf 1997; Hwang et al. 1998), providing strong constraint of the nucleosynthesis mechanism of Type Ia SNe.

X-ray studies with spatially-resolved spectroscopy were dramatically progressed in the last decade using the amazing angular resolution of Chandra and the large collecting area of XMM-Newton. The chemical stratification in the Tycho's SNR was confirmed even more clearly (Decourchelle et al. 2001). Also, the synchrotron X-rays from the forward shocks were separated from the thermal emission from the SN ejecta (Warren et al. 2005), offering more accurate measurements of elemental abundances. In Cas A, a jet-like feature of the Si-rich ejecta and asymmetric distribution of the Fe ejecta were revealed (Hughes et al. 2000). The bulk motions of the ejecta were also observed utilizing the superior resolution of Chandra (e.g., Hwang et al. 2001; Patnaude & Fesen 2007). The capabilities of these satellites also provided well-resolved images of Magellanic SNRs of which typical angular size is a few 10″ (1E 0102.2–7219: Gaetz et al. 2000; 0509–67.5: Warren & Hughes 2004) or even smaller (SN 1987A: Burrows et al. 2000). In addition, Chandra and XMM-Newton equip dispersive spectrometers which offers extremely high energy resolution, although the angular size of sources must be reasonably small to be observed. The development of hydrodynamical modeling applied to X-ray spectra of SNRs also helped provide strong constraint on the characteristics of the SN explosions (e.g., Badenes et al. 2003; 2006; Patnaude et al. 2012).

In 2005, Suzaku was put into orbit as the fifth X-ray astronomy satellite of Japan. Although the spatial resolution is not as good as those of Chandra and XMM-Newton, it has the improved energy resolution and high sensitivity especially in the 5–10 keV band for extended objects. These capabilities provides better studies of Fe-K emissions from SNRs as we demonstrate in the subsequent sections.

3. Difficulties in the abundance measurement and progenitor discrimination

A SNR contains stellar ejecta which radiate X-ray emission lines. Since the line intensity of each heavy element depends on its abundance, the X-ray spectra of SNRs tell us the amount of elements synthesized in the progenitor. However, the relation between the line flux and abundances is not always obvious. As an example, we show spectra of Tycho and W49B in Fig. 1. Tycho (a) is well known to be a Type

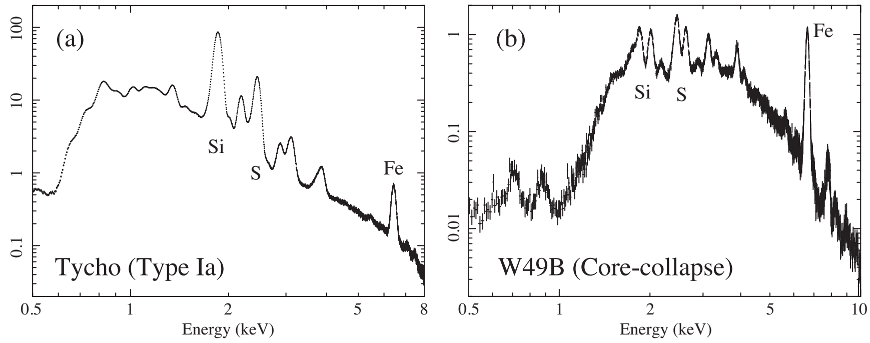

Fig. 1. Suzaku XIS spectra of Tycho (a) and W49B (b). Although Tycho is known to be a Type Ia remnant, the signature of Fe, a main product of a Type Ia SN, is relatively weak. On the other hand, the core-collapse SNR W49B exhibits the strong Fe K-shell emissions.

Ia SNR which contains a large amount of Fe (e.g., Nomoto et al. 1984), but the Fe K-shell emission is not very strong compared to the Si and S lines. The CC SNR W49B (b), on the other hand, exhibits strong Fe emissions with no signature of O, Ne, and Mg, although these are major products of a CC SN. Since the line intensity is determined not only from the total abundance but also from other physical parameters, such as the temperature and density, these values must be accurately measured. This is generally complicated, because the physical condition in SNRs is spatially inhomogeneous. Also, the foreground extinction may modify the soft X-ray spectrum, hence the information of the low-*Z* elements (i.e., O, Ne, Mg) can be concealed when the column density toward the SNR is large. This explains the weak evidence of these elements in the W49B spectrum.

Non-equilibrium ionization (NEI: e.g., Masai 1984) is another source of the difficulty in the abundance measurement. Fig. 2a shows the fraction of each Fe ion as a function of the electron temperature in a collisional equilibrium plasma. In the equilibrium case, the ion population depends only on the temperature, hence the abundance measurement is relatively straightforward. However, young SNRs evolving in tenuous interstellar space are generally in NEI, where the ion population depends on the ionization age as well. Since the line emissivity is different from charge number to charge number, precise determination of the ionization age is essential for the abundance measurement.

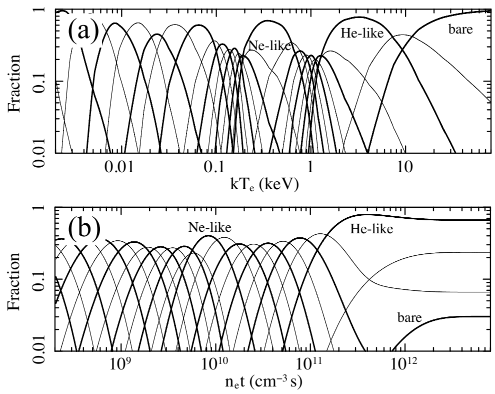

Fig. 2. (a) Ion population of Fe in an ionization equilibrium plasma as a function of the electron temperature. (b) Same as (a), but for a non-equilibrium (NEI) plasma with an electron temperature of 5 keV. The horizontal axis is the so-called ionization age, a product of the electron density and elapsed time since the gas was shock-heated.

Even if the elemental abundances are precisely measured, discrimination of the progenitor is still difficult. N103B in the LMC is one of SNRs of which the origin has been controversial. Analyzing XMM-Newton data, van der Heyden et al. (2002) concluded that this SNR has a core-collapse origin. However, their argument was objected by the later work (Lewis

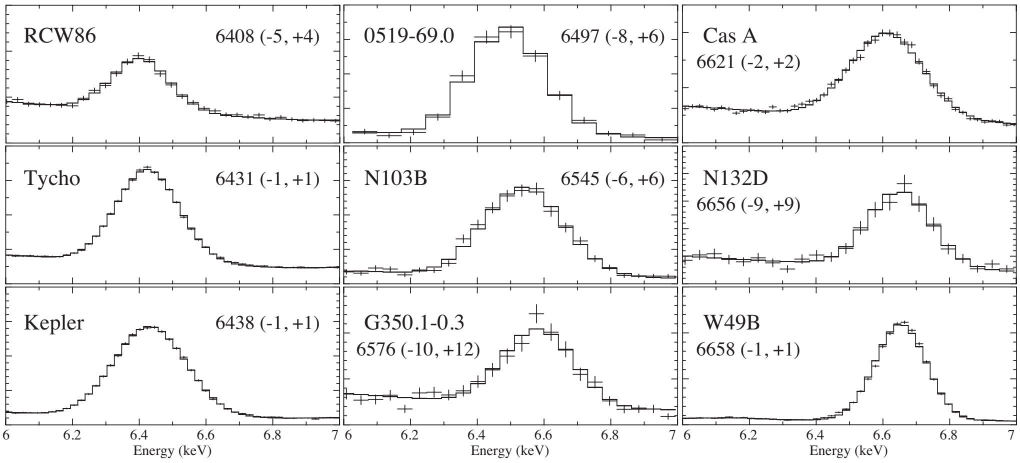

Fig. 3. Representative XIS spectra of the SNRs we studied. RCW86, Tycho, Kepler, 0519–69.0, and N103B are (possible) Type Ia remnants, while the others are CC ones. We find that the Type Ia SNRs generally show a lower centroid energy (or an ionization age) than CC SNRs.

et al. 2003). The primary reason of the discrepancy between the two results is related to the interpretation of the O K-shell emissions detected in the SNR's spectrum. The former work interpreted the origin to be the SN ejecta, while the latter concluded that this emission mainly originates from the swept-up circumstellar matter. As this example shows, it is not unusual that even the basic progenitor type of a SNR remains controversial.

Recently, Lopez et al. (2009; 2011) proposed a method to determine the SNR's origin from its X-ray morphology. They systematically analyzed high-resolution Chandra images of many SNRs and found that the CC SNRs are more spatially asymmetric than the Type Ia SNRs. However, one SNR (G344.7–0.1) classified as a CC SNR by their work was later found more likely to be a Type Ia remnant (Yamaguchi et al. 2012b). We may therefore need an alternative method for progenitor typing.

4. Systematic studies of Fe-K emission from SNRs with Suzaku

We here propose a simple method to classify a progenitor of young SNRs solely using the Fe K-shell emission. In young SNRs, the Fe emission is usually dominated by the ejecta of which an ionization age is sensitive to the ambient density (e.g., Badenes et al. 2007). In fact, several Type Ia SNRs in a low-density region show evidence of the low-ionized Fe ejecta (Tycho: Hwang et al. 1998; SN 1006: Yamaguchi et al. 2008; RCW86: Yamaguchi et al. 2011), while CC SNRs in a dense region exhibit K-shell emission from highly-ionized Fe (Cas A: Hughes et al. 2000; Sgr A East: Maeda et al. 2002). The aim of the present work is to investigate the property of Fe K-shell emission in other SNRs to understand how it depends on the progenitor type and their environment. The advantage of using Fe-K emission is that the line is well separated from other strong emissions, unlike Si and S K-shell lines which are mixed with each other under the typical energy resolution of CCD. Also, since the Fe ejecta in young SNRs are generally underionized (charge state is far below the He-like one), we can estimate the ionization age from the centroid energy of the Fe-K line.

We analyzed data of all SNRs that Suzaku has observed so far without any bias. 20 SNRs are found to exhibit clear Fe K-shell emission. Fig. 3 shows representative spectra. We found all the remnants that have an Fe-K centroid of less than 6.5 keV (a corresponding ionization age is $< 10^{10}\,\mathrm{cm^{-3}\,s}$) are Type Ia, while those with a higher centroid (> 6.6 keV or $> 10^{11}\,\mathrm{cm^{-3}\,s}$) are CC SNRs. Some SNRs (0519–69.0, N103B, G350.1–0.3, G292.0+1.8, 3C397) are in the intermediate region, but no overlap was observed. We investigated the line luminosity as well, and summarized the results in Fig. 4. More detailed information including the distance to the SNRs we assumed are given in a forthcoming paper (Yamaguchi et al. 2013, in preparation). We found that luminosity and centroid of the Fe-K emission are well correlated among each group of Type Ia or core-collapse remnants, and that the more luminous remnants tend to be more highly ionized.

Fig. 4 also gives the mean values for G1.9+0.3 and SN 1987A measured by Chandra (Borkowski et al. 2010) and XMM-Newton (Maggi et al. 2012) observations, respectively. We find the data point of G1.9+0.3 is closer to the Type Ia group, supporting the previous claim of the origin of this SNR (Borkowski et al. 2010). Interestingly, the Fe ions in SN 1987A are already highly ionized albeit its youngest age, suggesting the charge state of Fe is determined mainly in the initial phase of the SNR evolution.

It is worth noting that the highest centroid energy was observed in IC443 and W49B, both of which are known to have a recombining plasma where the average charge of ions is larger than that expected from the measured electron temperature, unlike a normal NEI plasma (Yamaguchi et al. 2009; Ozawa et al. 2009). This supports that the dominant charge state of the Fe ions strongly depends on the ambient density, given that the recombining plasma can be formed by interaction between the SN ejecta and dense circumstellar matter from a massive progenitor (e.g., Yamaguchi et al. 2012a; Moriya 2012).

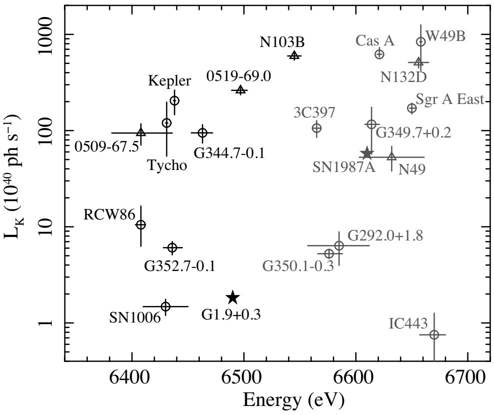

Fig. 4. Centroid energies and line luminosities of Fe K-shell emissions from various SNRs in our Galaxy (circle) and the LMC (triangle). Black and gray represent Type Ia and CC SNRs, respectively. The values for G1.9+0.3 and SN1987A reported by the preceding works (Borkowski et al. 2010; Maggi et al. 2012) are also indicated (star).

5. Summary and future prospects

X-ray observations of SNRs reveal the physics of stellar nucleosynthesis and SN explosion. However, temperature inhomogeneity, foreground extinction, and NEI effects often make the abundance measurement difficult. Interaction with ambient material also conceals the information of the pure ejecta. In this paper, we have demonstrated that our proposed method solely using the Fe K-shell emission can clearly discriminate the progenitor type. We have confirmed that the Fe ejecta in Type Ia SNRs are generally in the low ionization state, while the Fe in CC SNRs are highly ionized (or sometimes overionized). These are likely to be due to the pre-explosion density around the remnants.

To date, improvements of imaging and spectroscopic capabilities have complementarily developed our understanding of SNe and SNRs. Future development is also expected to proceed in a similar way. Non-dispersive high-resolution spectroscopy will be accomplished by a micro-calorimeter aboard ASTRO-H and following missions. This will allow us to explore more detailed physics concerning SNRs, such as thermal non-equilibrium between ions and electrons, and expansion velocity of shocked ejecta. A wide bandpass achieved by hard X-ray and soft γ-ray imagers of NuSTAR, ASTRO-H, and GRIPS will reveal accurate population of accelerated particles. It will also enable clear detection of radio active decay emissions: e.g., $^{44}\mathrm{Ti} \rightarrow {}^{44}\mathrm{Sc}$

at 67 keV and 78 keV, and $^{56}Ni \rightarrow ^{56}Co$ at 158 keV and 812 keV. These emissions provide a good probe for both SN type and asymmetricity in the explosion (e.g., Nagataki et al. 1998; Maeda et al. 2012). More advanced missions, like AXSIO, will achieve the sensitivity to extragalactic SNRs, which will dramatically improve our knowledge of SN explosion.

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