SEVEN CANDIDATES FOR SUPERNOVA REMNANTS EMITTING SYNCHROTRON X-RAYS AND THEIR RADIO PROPERTIES

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Abstract

Using the *ASCA* Galactic Plane Survey, we found seven candidates for shell-type supernova remnants (SNRs) emitting synchrotron X-rays. We have been making follow-up observations with *ASCA*, *Chandra* and/or *XMM-Newton*. As a result, for two candidates (G28.6−0.1 and G32.45+1.0), truly diffuse and shell-like structures were confirmed using high spatial resolution of *Chandra* or *XMM-Newton*. Three sources (G11.0+0.0, G25.5+0.0, and G26.6−0.1) were found to be extended larger than a point-source with *ASCA*, but observations with higher spatial resolution are required to determine whether they are shell SNRs or not. One source (G38.55+0.0) was observed with *XMM-Newton*, but no diffuse structure was detected, and no follow-up observation has been done for the last one (G23.5+0.1). We found that the parameters of three of those candidates (G25.5+0.0, G28.6−0.1, and G32.45+1.0) are similar to SN1006 and therefore we regard them as SNRs emitting synchrotron X-rays. Adding these sources to the radio Σ-D relation by Case & Bhattacharya (1998), we found that they are located in a radio faint region. One possible explanation is that SNRs efficiently accelerating high energy electrons are located in low density regions.

1 Introduction

Since cosmic rays were discovered by Hess (1912), the site of acceleration has been unknown. The energy spectrum of cosmic rays showering onto the earth is a single power-law up to $\sim 10^{15.5}$ eV where the power-law becomes steeper, and this energy region is called "knee." The origin of cosmic rays up-to "knee" has been thought to be galactic, and supernova remnants (SNRs) have been one of the strong candidates for the acceleration site.

The discovery of synchrotron X-ray emission from SN1006 (Koyama et al. 1995) was a breakthrough, showing there are high energy ($\sim$ 10 TeV) electrons in the shell of supernova remnants. However, whether shell-type SNRs are main contributors to the cosmic rays or not is yet unknown. The number of SNRs known to accelerate high energy electrons is small and systematic studies are yet to be done. In order to know how many SNRs are accelerating cosmic rays in our Galaxy and to enlarge the number of samples for systematic study of cosmic-ray accelerating SNRs, we search for SNRs emitting synchrotron X-rays using hard X-ray observations, a good tool for finding synchrotron X-rays. We abbreviate a "shell-type SNR emitting synchrotron X-rays" as an SXSNR hereafter.

Table 1: Summary of follow-up observations*

Candidates	*ASCA*	*Chandra*	*XMM*	Results†
G11.0+0.0	39 ks	-	-	△
G23.5+0.1	-	-	-	?
G25.5+0.0	37 ks	-	-	△
G26.6−0.1	36 ks	-	-	△
G28.6−0.1	71 ks	99 ks	-	○
G32.45+0.1	-	-	22 ks	○
G38.55+0.0	-	-	15 ks	×

*Exposures are listed for each satellites.
†The circles (○) indicate that truly diffuse and shell-like structures were confirmed. The triangles (△) indicate that X-ray emissions extended larger than a point-source were confirmed, but that they might not be SNRs. The cross (×) indicates extended X-ray emission was not confirmed. The question mark (?) shows no follow-up observation has been done.

2 The *ASCA* Galactic Plane Survey and follow-up observations

The *ASCA* Galactic Plane Survey (Yamauchi et al. 2002) covered an area of $|l| < 45°$, $|b| < 0.4°$ on the Galactic plane. Since *ASCA* was the first satellite that has imaging capability in the hard X-ray band (3–10 keV), this survey was effective in finding new hard X-ray sources that are deeply absorbed in the interstellar medium (ISM) and hence undetected in previous soft X-ray surveys.

From this survey, we searched for extended sources in the hard X-ray band, since they are candidates for SXSNRs. As a result, we found seven candidates, which were then followed up with *ASCA*, *Chandra*, and *XMM-Newton*, as shown in Table 1.

3 Properties of each source

In this section, we summarize the results of the follow-up observations first. And next, physical parameters of the candidates are compared with those of the prototype SXSNR, SN1006.

3.1 G28.6−0.1

With the *Chandra* observations of G28.6−0.1, we could resolve and remove point sources and a thermal clump from the main diffuse component. The spectrum of G28.6−0.1 can be fitted with a power-law function of photon index ∼ 2.1. Although the spectrum can also be fitted with a non-equilibrium thin thermal model, (an NEI model; Borkowski, Lyerly & Reynolds 2001a), the temperature was high (> 3.8 keV) and the abundance was low (< 0.34 solar) for an SNR (Ueno et al. 2003). Radio sources located in the region of the X-ray emission are reported by Helfand et al. (1989), with a total flux of ∼ 1 Jy (at 1.5 GHz).

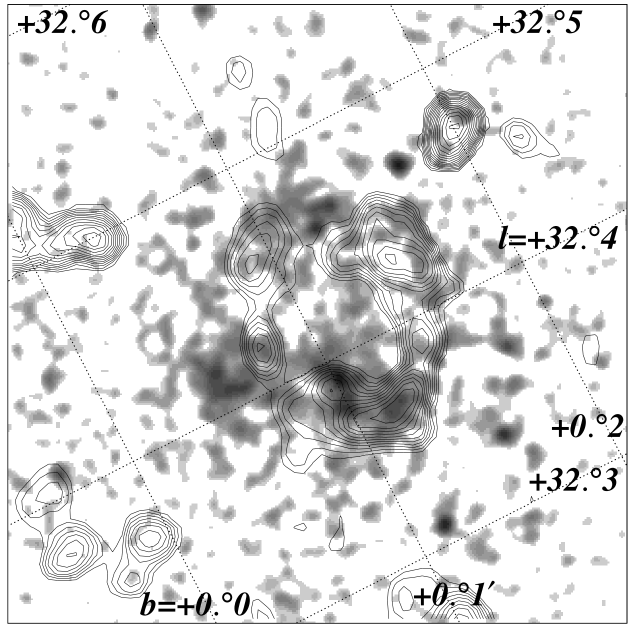

Figure 1: *XMM-Newton* gray-scale image of G32.45−0.1 in the hard X-ray band (2–7 keV). The contours show the intensity map of 20 cm radio continuum (NVSS; Condon et al. 1998).

3.2 G32.45+0.0

With the *XMM-Newton* observation, we could confirm a diffuse and shell-like structure in the hard X-ray band for G32.45+0.0 (Yamaguchi et al. 2004; Fig. 1). The spectrum can be modeled by a power-law function of photon index ∼ 1.5, which indicates non-thermal origin. Although an NEI model was also statistically acceptable, the temperature was high (> 7.3 keV) for an SNR. A shell structure was found at the same position in the 20 cm NRAO/VLA Sky Survey (NVSS) data (Condon et al. 1998; Fig. 1) and the total flux of the shell was ∼ 200 mJy.

3.3 G11.0+0.0, G25.5+0.0, and G26.6−0.1

With the deep observations with *ASCA* of G11.0+0.0, G25.5+0.0, and G26.6−0.1, their extended X-ray emissions were confirmed (Fig. 2). Their X-ray spectra are uniformly hard and featureless. When those

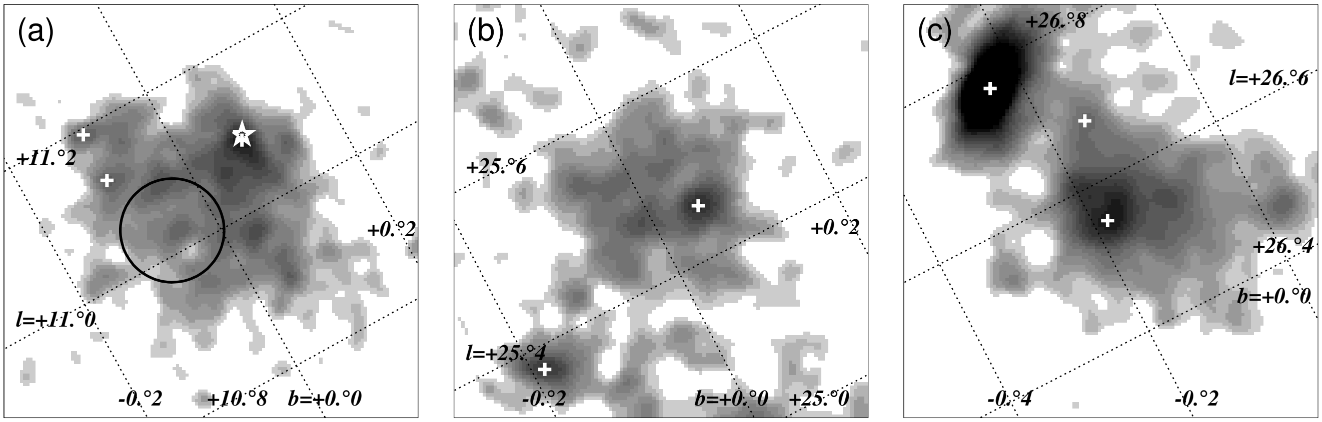

Figure 2: *ASCA* images of G11.0+0.0 (a), G25.5+0.0 (b), and G26.6−0.1 (c) in the hard X-ray band (2–7 keV). Point-sources detected in the energy band 0.7–7 keV with *ASCA* are designated with crosses. In figure (a), the position and size of G11.03−0.05 is shown with a circle, and the position of PSR 1809−1917 is shown with a star.

Table 2: Physical parameters of the SXSNR candidates

Candidates	D^*	$L_x^\dagger$	$\Gamma^\ddagger$	$E_{max}^\sharp$
G11.0+0.0	~ 13	0.37	1.6 (1.4–1.9)	~ 40
G25.5+0.0	~ 18	2.3	1.8 (1.6–2.2)	~ 20
G26.6−0.1	~ 4	0.081	1.3 (1.2–1.5)	~ 800
G28.6−0.1	~ 20	2.2	2.1 (1.8–2.5)	~ 7
G32.45+0.1	~ 22	2.1	1.5 (1.2–1.8)	~ 25
SN1006$^\flat$	~ 16	2.4	2.3 (1.8–2.6)	~ 30

*Diameter (pc).
†X-ray luminosity ($\times 10^{34}$ erg s^{-1}) in the energy band 0.7–10 keV.
‡Best-fit photon index of power-law functions with 90% error regions.
♯Maximum energy of electrons (TeV).
♭Physical parameters of SN1006 (Dyer, Reynolds & Borkowski 2004; Bamba et al. 2003b) are listed for comparison.

spectra were fitted with thermal plasma models, the temperatures became too high (> 6.8 keV) for thermal plasmas of SNRs. On the other hand, these spectra could also be fitted with power-law models, which suggest non-thermal emission, and these models are more reasonable than the thermal plasma models (Bamba et al. 2003a). Brogan et al. (2004) reported a radio SNR, G11.03−0.05, at the east part of G11.0+0.0 (Fig. 2a), whose association is not yet confirmed. As for G25.5+0.0 and G26.6+0.0, no radio counterparts were found in the NVSS data (Condon et al. 1998). The upper limit of the radio surface brightness is estimated to be $\sim 7\times10^{22}$ W m^{-1}Hz^{-1}sr^{-1} at 1.5 GHz.

3.4 Physical parameters of each source

Several physical parameters of the candidates are listed in Table 2. The distances were estimated from the X-ray absorption, assuming $n_{\rm H}$ = 1.0 cm^{-3}. We fitted each X-ray spectrum with a SRCUT model (Reynolds 1998) assuming spectral index at 1 GHz is 0.5, and determined cut-off frequencies. Maximum energies of electrons were calculated for a case that magnetic field strength (B) equals 10 μG using the relationship (Lazendic et al. 2004),

$$\nu_{\rm cutoff} \approx 1.61 \times 10^{16} \left(\frac{B}{10\ \mu{\rm G}}\right) \left(\frac{E_{\rm max}}{10\ {\rm TeV}}\right)^2\ {\rm Hz}. \quad (1)$$

The diameter and luminosity of G26.6−0.1 are much smaller than SN1006 (Dyer et al. 2004; Bamba et al. 2003b), a typical SXSNR, and this source is likely to be a kind of objects other than SXSNRs, for example, a pulsar wind nebula (PWN).

As for G11.0+0.0, the X-ray luminosity is low and there are two nearby radio sources, the pulsar, PSR 1809−1917 and the SNR, G11.03−0.05 (Morris et al. 2002; Brogan et al. 2004). We have to make an X-ray observation of higher spatial resolution to know what fraction of the X-ray emission is due to a putative PWN and the SNR detected in radio. Since G25.5+0.0, G28.6−0.1, and G32.45+0.1 have diameters, luminosities, and spectra similar to SN1006, we regard them as SXSNRs.

4 Discussion

4.1 Expected number of SXSNRs in the Galactic plane

From the *ASCA* Galactic Plane Survey, we discovered 3 SXSNRs. Since G347.3−0.5 [RXJ1713.7−3946] (Koyama et al. 1997) was also found from this survey, in total, 4 sources were discovered from the survey region of $|l| < 45°$, $|b| < 0.4°$. Here, 10% of the survey region suffered from stray light contamination from bright X-ray objects and had to be excluded. If we assume that the spatial number density of SNRs is uniform in the inner Galactic disk of the $|l| < 60°$, $|b| < 1°$, then the expected number of SXSNRs is $4\times1/(1-0.1)\times(120/90)\times(2/0.8) \sim 15$. Moreover, since the most distant SNR that we discovered is at 9 kpc, we expect a deeper survey can discover more distant and deeply absorbed SNRs.

4.2 Radio properties of SXSNRs

Case & Bhattacharya (1998, hereafter CB98) showed there is a relation between radio surface brightness (Σ) and diameter (D) of SNRs. We added the three newly found SXSNRs and 2 known SXSNRs (G347.3−0.5, G266.2−1.2; Koyama et al. 1997; Slane et al. 2001) to the plot of Σ versus D by CB98. The result is shown as Fig. 3. Among the SNRs cataloged by CB98, Cas A, Kepler's SNR, Tycho's SNR, and RCW86 are known to be SXSNRs (Vink & Laming 2003; Cassam-Chenaï et al. 2004; Hwang et al. 2002; Bamba, Koyama & Tomida 2000; Borkowski et al. 2001b). The distances of G349.7+0.2 and Tycho's SNR are updated to be 22 and 2.4 kpc, respectively, using recent observational results (Slane et al. 2002; Hughes 2000 and references therein). The diameter of G266.2−1.2 (Duncan & Green 2000) and the radio surface brightness of G25.5+0.0 (see Sect. 3) shown in Fig. 3 are upper limits.

From the plot, we can see that the SXSNRs ("△"s and "◯"s) can be roughly divided into two groups: SNRs with small Ds (Group A) and those with large Ds but faint in radio (Group B). Cas A, Kepler's SNR, and Tycho's SNR belong to Group A, and the 3 newly found SNRs, SN1006, and G347.3−0.5 belong to Group B. Since D roughly shows the age of an SNR, our revised Σ versus D relation indicates that young SNRs often emit synchrotron X-rays and as SNRs become older, most of them begin to stop emitting synchrotron X-rays, but a part of them, which are faint in radio, continue to emit synchrotron X-rays.

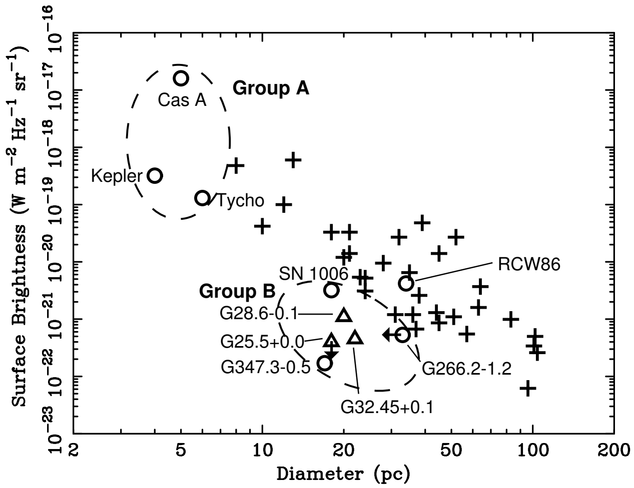

Figure 3: Σ versus D relation for shell SNRs revised from Fig. 1 of CB98. Newly found SXSNRs, known SXSNRs, and the other SNRs are designated with triangles (△), circles (◯), and crosses (+), respectively. The diameter of G266.2−1.2 and the radio surface brightness of G25.5+0.0 are upper limits. The SXSNRs except for RCW86 are divided into two groups: Group A and B (see text).

In any SNR, the synchrotron cut-off frequency ($\nu_{\rm cutoff}$) should be determined by balance between *acceleration rate* and *synchrotron loss rate*. If the acceleration time is long enough, $\nu_{\rm cutoff}$ is set by the condition *acceleration rate = synchrotron loss rate* (e.g., Uchiyama, Aharonian & Takahashi 2003). If we assume the electrons are accelerated by the diffusive shock acceleration (e.g., Malkov & Drury 2001 and references therein), we have, following the calculation by Uchiyama et al. (2003), a relation:

$$\nu_{\rm cutoff} \approx 5 \times 10^{17} \left(\frac{V}{2000\ {\rm kms^{-1}}}\right)^2 \eta^{-1}\ {\rm Hz}, \quad (2)$$

where V is the upstream velocity into the shock of an SNR and η is the gyrofactor. This relation indicates that whether synchrotron emission by high energy electrons is extending up-to the X-ray band (frequency of 2.4×10^{17} Hz corresponds to 1 keV) or not is determined only by the velocity of the shock (η is assumed to be ~ 1 and rather constant).

If we follow the discussion above, the shock velocities of the SNRs belong to Group B are large (≥ 2000 km s^{-1}) even though they have large Ds, which indicate they are relatively old and have swept up large size of interstellar medium. Then, when compared to SNRs with similar Ds, members of Group B should be located in low density regions. Our result, therefore, is consistent if SNRs in low density regions are faint in radio. In fact, such a correlation between Σ and ambient density was observationally shown by Berkhuijsen (1986).

Since the SNRs of Group A are young, their shock velocities are likely to be large and their synchrotron X-ray emissions can be explained in the same context. It should be noticed that their acceleration time scales are small compared with their ages. A remarkable difference between SNRs in Group A and those in Group B is that while thermal X-ray emissions are dominant in the former, non-thermal (synchrotron) X-rays are dominant in the latter, and it may show difference of acceleration efficiency between them. RCW86, whose radio brightness is slightly larger than Group B, emits non-thermal and thermal X-rays with comparable luminosities. RCW86 may reside in a peculiar situation, for example, expanding inside a cavity and a part of the shell is encountering the wall (e.g., Dickel, Strom & Milne 2001 and references therein). Quantitative conditions (the ambient density, the age, and so on) which determine luminosities of synchrotron X-rays should be a future work.

Lastly, our discoveries of new SNRs suggest that a hard X-ray survey is a strong way to find SNRs, mainly those emitting synchrotron X-rays which is likely to be faint in radio. Follow-up observations of the candidates found in the *ASCA* survey are encouraged to test existence of radio-faint SNRs embedded on the Galactic plane and to know their emission mechanism.

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