X-ray observations of supernova remnant G54.1+0.3: X-ray spectrum and the discovery of an X-ray jet

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Abstract. We present in this paper analyses of the ROSAT PSPC and ASCA SIS and GIS observations of the Crab-like supernova remnant (SNR) G54.1+0.3. Its spectrum obtained by ROSAT PSPC favors a power law model with a photon index of $-0.8^{+0.8}_{-2.0}$ absorbed energy flux in $0.1-2.4$ keV of $1.0 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, and absorption column density of $12.3^{+8.0}_{-3.2} \times 10^{21}$ cm$^{-2}$. ASCA SIS observation shows that its spectrum can also be best fitted with power law model. The fitted parameters are, photon index $-1.9^{+0.1}_{-0.2}$, absorbed energy flux in $0.7-2.1$ keV $6.5 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, and column density $17.9^{+2.8}_{-2.5} \times 10^{21}$ cm$^{-2}$. The high absorption column density indicates a distance similar to the radius of the galaxy. The $0.1-2.4$ keV X-ray luminosity of G54.1+0.3 is $3.2 \times 10^{33} d_1^{2}$ erg s$^{-1}$, where $d_1$ is the distance in 10 kpc. With an image restoration method we have obtained high spatial resolution X-ray image of the remnant, which clearly shows an X-ray jet pointing to the northeast with a length about 40$''$ from the center of the nebula. Its X-ray luminosity in $0.1-2.4$ keV is about $5.1 \times 10^{32} d_1^{2}$ erg s$^{-1}$. The X-ray jet is consistent with the radio extension to the northeast in both direction and position. We propose that the X-ray jet is connected with the pulsar assumed to exist in the remnant.

Key words: X-ray: ISM – ISM: supernova remnants – ISM:jet and outflows – ISM: individual: G54.1+0.3

1. Introduction

Radio source G54.1+0.3 was first suggested to be a Crab-like SNR by Reich et al. (1985) for its flat spectral index of $\alpha \sim -0.1 \pm 0.1$, filled-center morphology and significant polarization. This identification to G54.1+0.3 was confirmed by Velusamy & Becker (1988) with high resolution multifrequency observations with the VLA and OSRT. In the high resolution VLA maps, G54.1+0.3 has a filled-center brightness distribution peaks around R.A.(2000) =19:30:30, DEC(2000)=18:52:11 and extends to the northeast and north (Velusamy & Becker 1988). They pointed out that these extensions are reminiscent of the radio jets seen in the Crab (Velusamy 1984), CTB80 (Angerhofer et al. 1981) and G332.4+0.1 (Roger et al. 1985).

X-rays from G54.1+0.3 was detected by EINSTEIN IPC (resolution ~ 1$'$) with a source strength of $0.016 \pm 0.004$ counts s$^{-1}$ in the energy band $0.5-4.0$ keV (Seward 1989). No extent to the X-ray emission was found, due to both its small angular size ($2.0' \times 1.2'$) (Velusamy & Becker 1988) and its low flux. A power law spectral fitting with energy index of 1.0 gives column density $N_H$ between $5 \times 10^{21}$ and $1 \times 10^{23}$ cm$^{-2}$, with the best fit value of $3 \times 10^{22}$ cm$^{-2}$, indicating a large distance of this source.

In the paper we present the analyses of ROSAT PSPC and ASCA GIS and SIS observations of G54.1+0.3. We obtain its spectral information, and, with the aid of an image restoration method, we obtain a high spatial resolution X-ray map of the remnant which clearly shows an X-ray jet pointing to the northeast.

2. Observations and analysis method

The ROSAT PSPC pointing observation of SNR G54.1+0.3 was carried out from April 11th to 18th, 1991 with a total acceptable observational time of 20271 seconds. We use EXSAS (Zimmermann et al. 1998) to analyze its spectrum and produce a $0.1-2.5$ keV X-ray image (figure 1) whose spatial resolution is the intrinsic resolution of PSPC ($40''$).

G54.1+0.3 was also observed with ASCA observatory (Tanaka et al. 1994) continuously from April 27th to 28th, 1997, using the two Gas Imaging Spectrometers (GIS-2 and GIS-3) and the two Solid State Imaging Spectrometers (SIS-0 and SIS-1). Data were collected by the two GIS detectors with a photon time-of-arrival resolution of $4.88 \times 10^{-4}$ s in the high bit-rate modes. An effective exposure time of 16.5 ks was achieved for each detector. The GIS detectors were operated in the 1-CCD faint mode in which read-out is every 4 s. All GIS data were filtered using the standard screening criteria, which resulted in effective exposures of 19 ks and 20.7 ks for SIS-0 and SIS-1 respectively. Since the two GIS detectors were operated in the high time-of-arrival resolution model, we used the GIS data for temporal analysis. The GIS detectors which are sensitive to photons in 0.5-10.0 keV have superior energy res-
olution compared to the GIS, and so the SIS data are used for spectral analysis.

Due to the small angular size (120′′ × 75′′) of G54.1+0.3 and the limited spatial resolution (∼40″) of PSPC, the PSPC observation cannot directly give even a coarsely resolved image of G54.1+0.3. In order to obtain an image with higher spatial resolution, we use the widely used Lucy-Richardson formula (Richardson 1972, Lucy 1974) to eliminate the point spread function effect in figure 1. In the iteration process we have used the mean background as the lower limit constraints, in order to improve the quality of the restored image, as done by Li & Wu (1994), Lu et al. (1996) and Zhang et al. (1998).

3. Results

3.1. Spectrum from ROSAT PSPC observation

The ROSAT PSPC spectrum of G54.1+0.3 shows a lack of low energy photons and peaks at energy channel 150 (about 1.5 keV). The spectrum can be fitted with power law model and Raymond-Smith (1977) thermal plasma model. The power law model yields a photon index of -0.8 with 1σ error range of -2.8 to 0.0 and an absorption column density of 12.3 × 10^{21} cm^{-2} with 1σ error range of 8 to 20 × 10^{21} cm^{-2} (see figure 2). The thermal plasma model derives a plasma temperature of 1.8 keV (>1.2 keV) and absorption column density of 21.1 × 10^{21} cm^{-2} with 1σ error range of 15-26 × 10^{21} cm^{-2}. The reduced χ² values are almost the same, 0.831 for power law model and 0.834 for thermal plasma model. We adopt the power law model in this paper for it gives the best and the most reasonable fit to the ASCA SIS spectrum, as shown in the next section. It gives the absorbed and unabsorbed 0.1-2.4 keV X-ray energy fluxes of 1.0 × 10^{-12} and 3.4 × 10^{-12} erg cm^{-2} s^{-1}, respectively. Figure 3 shows the power law model fitting results.

Fig. 1. Count-rate map in 0.1-2.5 keV obtained by ROSAT PSPC observation to G54.1+0.3. North is up and east is left. The contours overlaid represent the smoothed count-rate map with a 10″ FWHM Gaussian filter. The contour intervals are linear in step of 10^{-5} count s^{-1} per 2′×2′ pixel. The lowest contour corresponds to a brightness level of 10^{-5} cnt s^{-1} per pixel.

Fig. 2. χ² distribution on the column density–photon index plan of the power law spectral fitting of ROSAT PSPC observation of G54.1+0.3. Contours from the inner to the outer correspond to 1σ to 5σ.

Fig. 3. Spectral fitting results to the X-ray emission of G54.1+0.3 obtained by ROSAT PSPC with a power law model. The parameters are presented in the text.

3.2. Spectrum from ASCA SIS observation

The SIS spectra of the source were extracted within a 4.5 arcminutes radius region. After subtracted the source region, another region of the CCD was used for background subtraction. The source and background spectra obtained from both SISs were added to obtain improved statistics. The spectral analyses
software is XSPEC. Energies above 8 keV were not used because of the poor signal to noise ratio. We have used power law, blackbody, single temperature bremsstrahlung and Raymond-Smith thermal plasma models to fit the spectrum, and found that only the power law model and the thermal bremsstrahlung model give acceptable and reasonable fits. The obtained parameters of the power law model are: photon index $\alpha \sim -1.9^{+0.2}_{-0.2}$, column density $N_H \sim 17.9^{+2.8}_{-2.3} \times 10^{21}$ cm$^{-2}$, 0.7-2.1 keV energy flux $6.5 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, reduced $\chi^2$ 0.7. Parameters of a thermal bremsstrahlung model are: temperature $T_e \sim 7.9^{+3.9}_{-3.1}$ keV, column density $N_H \sim 15.4^{+2.0}_{-1.3} \times 10^{21}$ cm$^{-2}$, 0.7-2.1 keV energy flux $8.6 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, reduced $\chi^2$ 0.8. We choose the power law model in this paper for that it has the smallest $\chi^2$ and a power law X-ray spectrum is the typical property of the X-ray emission of a Crab-like SNR. For illustration, we show in figure 4 the best fit power law model and its residuals.

![Spectral fitting results to the X-ray emission of G54.1+0.3 obtained by ASCA SIS with a power law model. The parameters are presented in the text.](image)

**Fig. 4.**

3.3. Temporal analysis

We examined the ASCA GIS data for temporal variability by extracting photons from a 6 arcminutes radius circle centered on the source. A search for coherent pulsations from the source was made by combing the two GIS high-time-resolution data sets (time resolution $4.88 \times 10^{-4}$ s) and the arrival times of the used 1805 photons were barycentered. We performed a restricted search for periodic signals between 0.01 s and 2 s using a folding technique (20 phase bins per fold), and detected no pulsation with a significance of more than 3$\sigma$ in this period range.

3.4. Image restoration results

The distribution of photons detected by ROSAT PSPC peak at 1.5 keV and is quite symmetric. We thus use the PSPC point spread function in 1.5 keV and the method described in section 2 to restore the original image (figure 1). The iteration stops after 50 iterations (indeed the restored image is insensitive to the iteration number after 20 iterations). The restored image is shown in figure 5, in which a jet-like feature (hereafter JLF) pointing to the northeast appears, in addition to the $\sim$30$''$ diameter bright nebula coinciding with the brightest radio region. The angular distance from the head of the JLF to the center of the central bright nebula is about 40$''$. The total photon flux of the bright nebula is $2.07 \times 10^{-2}$ counts s$^{-1}$, that of the JLF is $3.9 \times 10^{-3}$ counts s$^{-1}$, about 430 and 80 photons have been detected from the bright nebula and JLF respectively.

![Restorated 0.1-2.5 keV X-ray intensity map of G54.1+0.3. North is up and east is left. The contour intervals are linear with a step size of $4 \times 10^{-5}$ cnt s$^{-1}$ per 2$''$ x 2$''$ pixel. The lowest contour corresponds to a brightness level of $2 \times 10^{-5}$ cnt s$^{-1}$ per pixel.](image)

**Fig. 5.**

In order to exam the reliability of the restored image, we have performed a Monte-Carlo simulation. Figure 6(a) displays an object similar to G54.1+0.3 in figure 4 in shape and flux. Figure 6(b) is the simulated ROSAT PSPC observational result with the same observing time and background level as the real observation to G54.1+0.3, and figure 6(c) is the smoothed image from 6(b). Figure 6(d) is the restored image of 6(b). The simulation shows that the high resolution X-ray image of G54.1+0.3 we obtained is reliable.

4. Discussions

4.1. Distance and X-ray luminosity of G54.1+0.3

Velusamy & Becker (1988) suggested that G54.1+0.3 may have a distance of about 3.2 kpc, if its progenitor is in the star-forming region G53.9+0.3. The galactic HI column density in this direction is about $14.5 \times 10^{21}$ cm$^{-2}$ (Dickey & Lockman 1990). The best fit column density we get from ROSAT PSPC...
4.3. X-ray jet

For the first time an well resolved X-ray image of G54.1+0.3 has been obtained. It shows a JLF pointing to the northeast. The simulation shows that such a structure can be clearly resolved by ROSAT PSPC with the aid of an image restoration technique. The simulation also shows that this feature can not be attributed as the fluctuations of the bright source, it is an intrinsic structure of the object.
We have studied the possibility that the JLF is indeed a separate object lies in a similar direction with G54.1+0.3. We find that there is no identified object in the 30′′ vicinity of the JLF except G54.1+0.3. The optical plate obtained by Palomar Observatory Sky Survey and electronically reproduced by Skyview of NASA/GSFC shows no source in the JLF region too. The JLF shown in figure 5 shows some enhancements in the head. But it might be a false phenomenon caused by the low quality of the original data and the restoration process, as can be found in the simulation, although some similar structures exist in the 4.8 GHz radio map. More simulations show that the length of the JLF is quite reliable, the width of the JLF might have an uncertainty up to ~50%.

We have compared figure 4 with the 4.8 GHz VLA map obtained by Velusamy & Becker (1988) in details. The brightest point of the extended X-ray source locates at R.A.(2000)=19:30:30.0, DEC(2000)=18:52:07, which coincides with the brightest region of the radio source. The head of the JLF has a coordinate of R.A.(2000)=19:30:32.2, DEC(2000)=18:52:31, which also coincides with the northeastern enhancement in the radio map. The nice position coincidence of the X-ray and radio sources strongly favor their same origin. However, the X-ray source has a smaller extent than the radio source and no significant X-ray emission has been detected along the northward feature, which was suggested to be the most probable radio JLF by Velusamy & Becker (1988). It might be due to the intrinsic deficiency or the limited sensitivity of the present observation.

There are two possible ways to explain the origin of the X-ray JLF. One is that it is a fragment produced in the supernova explosion, like the fragments detected around the Vela SNR, especially its ‘bullet’-like fragment A. (Aschenbach et al. 1995; Strom et al. 1995). However, significant radio emission has only been detected around the head of the fragments, implies that most of the relativistic electrons are in the leading edge of the fragments, close to the shock front (Strom et al. 1995). But in the case of G54.1+0.3 the radio emission has a similar distribution with the X-ray JLF, indicating a similar distribution of relativistic electrons with the X-ray brightness. It makes the fragment origin of the X-ray JLF implausible. The second is that the X-ray JLF is due to the relativistic electrons produced by the central pulsar, like X-ray jets detected in PSR 1929+10 (Wang et al. 1993). Crab SNR (Hester et al. 1995), Vela pulsar (Markwardt & Ögelman 1995), SNR MSH 15-52 (Tamura et al. 1996), SNR CTB80 (Wang & Seward 1984; Safi-Harb et al. 1995) in the galaxy and SNR N157B in the Large Magellanic Cloud (Wang & Gotthelf 1998). The coincidence of radio and X-ray emission in the case of Vela pulsar jet (Frail et al. 1997) and that of SNR N157B (Wang & Gotthelf 1998) strongly support this scenario. We conclude that the JLF we discovered is quite probably an X-ray jet connected with the pulsar in G54.1+0.3.

The X-ray emission of Vela pulsar jet can be fitted with both power law and thermal plasma model (Markwardt & Ögelman 1995), and the X-ray pulsar jet in MSH15-52 appears to be nonthermal. It is difficult to get the spectral properties of the X-ray jet in G54.1+0.3 with the present data. We assume that it share the same power law model with the whole remnant, and is due to the synchrotron radiation of relativistic electrons from the pulsar. The X-ray luminosity of the jet in 0.1-2.4 keV is then about $5.1 \times 10^{32} d_{10}^2$ erg s$^{-1}$.

From the radio map of Velusamy & Becker (1988) we estimate that the flux of the jet at 4.8 GHz is about 40 mJy. Its X-ray flux at 1 keV is about $9.4 \times 10^{-5}$ mJy. The two fluxes give a spectral index from radio to X-ray of about -0.73, quite similar to that of the whole remnant.

The distance of the jet head to the nebula center is about 40′′. It corresponds to 2 pc if the SNR is 10 kpc away. Recent distance measurements to Vela SNR obtained a distance of 250±30 pc (Cha et al. 1999). If so the Vela pulsar jet is about 3 pc long (Cha et al. 1999, Markwardt & Ögelman 1995). The lengths of the two jets are quite similar.

5. Summary

ROSAT PSPC and ASCA observations of G54.1+0.3 imply a large distance comparable with the galactic radius. Its X-ray spectrum is of nonthermal origin. The comparison of the radio and X-ray emissions shows that the energy distribution of the relativistic electrons has a break around 300 GeV. This break is quite probably an intrinsic property of the relativistic electrons from the central pulsar instead of due to the energy lose in the synchrotron radiation process, if G54.1+0.3 is not as old as $3.7 \times 10^7$ years.

A high spatially resolved image shows an X-ray jet pointing to the northeast, similar to the radio structures. Its nonthermal spectrum and the existence of X-ray jet confirm the formal identification of G54.1+0.3 as a Crab-like SNR, though no pulsation has been found in the X-ray observation. Future deep X-ray observations with high spatial resolution and spectral resolution telescopes such as Chandra and XMM are invaluable to find out the spectral and spatial structure of the remnant as well as the X-ray jet.

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