New identification of the mixed-morphology supernova remnant G298.6−0.0 with possible gamma-ray association

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Abstract

We present an X-ray analysis on the Galactic supernova remnant (SNR) G298.6−0.0 observed with Suzaku. The X-ray image shows a center-filled structure inside a radio shell, implying that this SNR can be categorized as a mixed-morphology (MM) SNR. The spectrum is well reproduced by a single-temperature plasma model in ionization equilibrium, with a temperature of 0.78 (0.70–0.87) keV. The total plasma mass of $30 M_\odot$ indicates that the plasma has an interstellar medium origin. The association with a GeV gamma-ray source, 3FGL J1214.0−6236, on the shell of the SNR is discussed, in comparison with other MM SNRs with GeV gamma-ray associations. It is found that the flux ratio between absorption-corrected thermal X-rays and GeV gamma-rays decreases as the physical size of MM SNRs becomes larger. The absorption-corrected thermal X-ray flux of G298.6−0.0 and the GeV gamma-ray flux of 3FGL J1214.0−6236 closely follow this trend, implying that 3FGL J1214.0−6236 is likely to be a GeV counterpart of G298.6−0.0.

Key words: gamma-rays: ISM — ISM: individual (G298.6−0.0, 3FGL J1214.0−6236) — ISM: supernova remnants — X-rays: ISM

1 Introduction

The origin of Galactic cosmic rays has been remaining an unresolved question since their discovery. One of the most plausible acceleration sites is at the shock front of supernova remnants (SNRs). The discovery of synchrotron X-rays (Koyama et al. 1995) and very high-energy (VHE) gamma-rays (Aharonian et al. 2004) from shells of SNRs provided some of the first clear evidence of active particle acceleration in these shocks. The small-scale structure and time variability of synchrotron X-rays imply that the acceleration is very efficient (Bamba et al. 2003, 2005; Uchiyama et al. 2007). However, it remains an open question as to how accelerated particles escape from the shocks to become cosmic rays.

Recently, Fermi detected GeV gamma-rays from several SNRs (Abdo et al. 2010a, 2010b, 2010c). Interestingly,
many of the GeV-detected SNRs are many times older than the nonthermal X-ray-detected or VHE-gamma-ray-detected SNRs (S. Funk 2011). Moreover, their GeV spectra are soft and show a spectral break at energies of around 1–10 GeV, implying that high-energy particles have already lost energy, or have escaped from the acceleration sites. If the latter is true, their soft spectra show evidence of particle escape. However, a larger sample of GeV gamma-ray SNRs is needed to judge the particle-escape scenario.

We searched for GeV gamma-ray sources associated with cataloged Galactic SNRs in the Fermi Large Area Telescope Third Source Catalog (Acero 2015). There are sixty GeV gamma-ray sources that spatially coincide with the Galactic SNRs, in addition to twelve SNRs identified by their extended gamma-ray emission. 3FGL J1214.0−6236 is associated with the radio SNR G298.6−0.0, detected at 408 MHz and 843 MHz with a flat radio spectral index of −0.3 (Shaver & Goss 1970; Kesteven & Caswell 1987; Whiteoak & Green 1996). Reach et al. (2006) reported on a possible detection of infrared emission from the direction of G298.6−0.0, implying that the shock of this remnant may have encountered a high-density medium. These characteristics are common among GeV gamma-ray-emitting SNRs. However, no detection has been made in the X-ray band with ROSAT PSPC (Hwang & Markert 1994). X-ray information is critical in estimating physical parameters of the SNR, such as the age, the explosion energy, and the amount of accelerated electrons. Thus, our aim is to identify X-rays from G298.6−0.0 and to measure their parameters using the low, stable background X-ray observations provided by Suzaku (Mitsuda et al. 2007).

In this paper, we report on the first X-ray imaging spectroscopy of G298.6−0.0 using Suzaku. The observation details are summarized in section 2. An analysis of the Suzaku X-ray data is presented in section 3, the results of which are discussed in section 4.

2 Observations and data reduction

Suzaku observed G298.6−0.0 on 2012 August 11–13 (sequence number: 507037010) and 2013 February 18–19 (sequence number: 507037020). Only three sets of the onboard X-ray Imaging Spectrometers (XIS 0, 1, 3: Koyama et al. 2007) could be used in the present work, due to a known problem with XIS 2. XIS 1 is a back-illuminated CCD, whereas the others are front-illuminated. The XIS instruments were operated in the normal-clocking full-frame mode. A spaced-row charge-injection technique and the relevant energy calibration method were applied to mitigate the long-term degradation of the energy resolution (Uchiyama et al. 2009). Since the observing mode was the same for the two observations, we analyzed the combined data using HEADAS software version 6.16 and XSPEC version 12.8.2. We reprocessed the data set with the calibration database version 2012-11-06 for XIS and 2011-06-30 for X-ray Telescope (XRT: Serlemitsos et al. 2007).

In the XIS data screening, we filtered out the data acquired during the passage through the South Atlantic Anomaly (SAA), having elevation angles with respect to Earth’s dark limb below 5°, or with an elevation angle to the bright limb below 20° in order to avoid contamination by emission from the bright limb. The remaining exposure was 57 ks (17 ks for the former observation and 40 ks for the latter observation).

3 Results

3.1 Images

Figure 1a shows 843 MHz (Whiteoak & Green 1996) and the XIS 1+3 0.5–5 keV band images of the G298.6−0.0 region. An XIS 0 image is not used due to the dead column. The position of the Fermi source, 3FGL J1214.0−6236, is also shown. The radio emission shows a clear shell-like structure, while X-ray emission has a center-filled morphology inside the radio shell, and does not show any prominent point sources. These results show that G298.6−0.0 is either an SNR with a central pulsar or a mixed-morphology SNR (MM SNR: Rho & Petre 1998). The point source located in a northeasterly direction of the SNR is coincident with the ROSAT source 1RXS J121248.7−623027 (Fuhrmeister & Schmitt 2003), and is categorized as a rotationally variable star (Kiraga 2012), whose details are out of the scope of this paper.

3.2 Spectra

The source spectra of G298.6−0.0 were extracted from a circular region with a radius of 3.9′, whereas the background spectra were taken from the source-free region, as shown in figure 1b. We added XIS 0 and XIS 3 spectra for better statistics, whereas the XIS 1 spectrum was treated separately due to the different response from the others.

Background-subtracted spectra are shown in figure 2. The spectra are rather soft, and have emission lines, implying that the emission has a thermal origin. We thus adopted an optically thin thermal plasma model in collisional ionization equilibrium (VAPEC) affected by interstellar absorption (PHABS: Balucinska-Church & McCammon 1992). For both the emission and absorption models, the solar abundance values of Anders and Grevesse

1 Funk, S. 2011, presentation at TeV particle Astrophysics 2011 (AlbaNova University Center, Stockholm).
Fig. 1. (a) The 843 MHz (contours) and 0.5–5 keV (gray scale) images of the G298.6−0.0 region. The X-ray image is smoothed with a Gaussian function having the kernel of 0′.4. Non–X-ray background (NXB) was not subtracted, and no vignetting correction was performed. The color scale is on the logarithmic scale. The red circle shows the error region of the Fermi source, 3FGL J1214.0−6236. The coordinates are in J2000.0. The point source in the northwesterly direction is 1RXS J121248.7−623027 (Fuhrmeister & Schmitt 2003). (b) Same image as (a) with source (bold) and background (thin) regions for the spectral analysis.

Fig. 2. Background-subtracted spectra of the source region. Black and red crosses represent the FI and BI spectra, respectively. The solid lines represent the best-fitting VAPEC model.

(1989) were used. The first trial fitted with abundances fixed at the solar values was rejected due to a reduced $\chi^2$ of 228.6/117 and to wavy residuals. We thus made a fit with the abundances of Mg, Si, S, and Fe as free parameters. This improved fit gave a reduced $\chi^2$ of 136.1/113. The best-fitting models and parameters are given in figure 2 and table 1, respectively. We also tried to make a fit with non-equilibrium ionization plasma models, VNEI for ionizing plasma and VVRNEI for recombining plasma. The abundances of Mg, Si, S, and Fe were treated as free parameters. For a VVRNEI model, we fixed the initial plasma temperature at 3 keV. The fitting showed similar reduced $\chi^2$ values of 136.5/112 (VNEI) and 131.5/112 (VVRNEI). The best-fitting values of the ionization/recombination timescale are $>9.8 \times 10^{11}$ s cm$^{-3}$ for the VNEI model and 6.2 (5.3–14) $\times 10^{11}$ s cm$^{-3}$ for the VVRNEI model. The latter gives a slightly shorter relaxation timescale than that in ionization equilibrium ($10^{12}$–$13$ s cm$^{-3}$). However, the improvement of the fitting is only marginal; both models show similar reduced $\chi^2$ values. Moreover, there is no clear indication of a strong radiative recombination continuum in the residual, which is direct evidence of a recombining plasma (Yamaguchi et al. 2009). We thus concluded that the plasma is well described by an absorbed plasma emission

| Table 1. Best-fitting parameters of the spectral fitting (VAPEC).$^*$ |
|-------------------------|-----------------|
| Parameter Value |
| $N_H$ (10$^{22}$ cm$^{-2}$) | 1.65 (1.45–1.99) |
| $kT$ (keV) | 0.78 (0.70–0.87) |
| Mg | 0.59 (0.39–0.86) |
| Si | 0.38 (0.27–0.50) |
| S | 0.35 (0.21–0.50) |
| Fe | < 0.23 |
| $EM^\dagger$ | 5.6 (4.1–8.1) |
| Reduced $\chi^2$ | 136.1/113 |

$^*$Errors indicate the single parameter 90% confidence interval.

$^\dagger$Emission measure in units of $10^{-11}(4\pi D^2)^{-1}\int n_e n_H dV$ cm$^{-5}$, where $D$, $n_e$, and $n_H$ represent the distance and electron and hydrogen densities.
model in ionization equilibrium. We note that the XIS 1 spectrum has residuals in the low-energy band, which may be due to the uncertainty in calibration of contamination.

4 Discussion

4.1 Physical parameters of G298.6−0.0

We report on the first detection of thermal X-rays from the inside of the radio SNR G298.6−0.0. According to the characteristics of G298.6−0.0, it is classified as a new MM SNR. Here, we estimate its several physical parameters.

First, we estimate the distance to this source. We measured the absorption column to the source to be 1.65 (1.45−1.99) × 10^{22} cm^{-2}. The total hydrogen density throughout the Galaxy in this direction is estimated by a method of Willingale et al. (2013). The H\textsc{i} column density in this direction is 1.4 × 10^{22} atoms cm^{-2} (Kalberla et al. 2005), whereas the column density of molecular hydrogen (H\textsubscript{2}) is 1.4 × 10^{21} atoms cm^{-2} based on a dust map (Schlegel et al. 1998). The total absorption column is thus 1.5 × 10^{22} atoms cm^{-2}, which is a similar value to our target. This indicates that the SNR is located in the outer part of the Galaxy. According to a face-on map by Nakanishi and Sofue (2006), most of the interstellar hydrogens in this direction are located within 10 kpc from the Sun. We thus adopt a distance of 10 kpc. This is an independent constraint of that indicated by the \Sigma−D relation in the radio band (9.5 kpc: Case & Bhattacharya 1998). The previous method only gives a rough estimate, and more detailed studies are necessary for obtaining a more accurate measurement of the distance to SNR G298.6−0.0.

Assuming that the plasma fills a 3:9 sphere, the total volume is 1.8 × 10^{59} D_{10}^{3/2} cm\textsuperscript{3}, where D\textsubscript{10} is the distance in units of 10 kpc. The average density derived from the emission measure (table 1) is 0.2 D_{10}^{1/2} f^{1/2} cm\textsuperscript{-3}, where f is the filling factor. The total mass and thermal energy can be estimated at 30 D_{10}^{1/2} f^{1/2} M\odot and 6.4 × 10^{49} D_{10}^{1/2} f^{1/2} erg, respectively. The large total mass indicates that the main component of the plasma originates in a swept-up interstellar medium.

4.2 Comparisons of G298.6−0.0 and other SNRs with GeV counterpart

Here, we discuss comparisons between G298.6−0.0 and other MM SNRs with GeV gamma rays, to judge whether 3FGL J1214−6236 has similar properties to other GeV counterparts of MM SNRs.

GeV emission is coincident with the shell of G298.6−0.0, which is the same as other SNR cases (Abdo et al. 2010a). The possible interaction with a high-density medium in the direction of this SNR has been reported (Reach et al. 2006), which is also similar to other GeV SNR samples. On the other hand, we have no information about which part of this SNR interacts with the high-density medium. Further studies in the infrared or molecular-cloud bands are needed to make any conclusion about the interaction. The GeV spectrum of 3FGL J1214−6236 has a spectral break at around a few GeV (Acero 2015), which is also similar to the spectra of other GeV SNRs. These facts imply that 3FGL J1214−6236 is a possible GeV counterpart of G298.6−0.0.

Table 2 gives a summary of the properties along the absorption-corrected 0.3−10 keV and 0.1−100 GeV bands of the GeV gamma-ray emitting MM SNRs. Considerable uncertainties in distance for these sources make it difficult to apply a detailed model of the X-ray and GeV gamma-ray evolution to the case of G298.6−0.0. Instead, we compare the flux ratio between absorption-corrected X-rays and GeV gamma-rays, which is independent of the distance.

| Sample | D\textsubscript{10} | Radius | F\textsubscript{X} | F\textsubscript{G} | F\textsubscript{X}/F\textsubscript{G} | References |
|--------|----------------|--------|-------------|-------------|-----------------|------------|
| W 49 B | 8              | 5.1 ± 0.7 | 56^2        | 1.8         | 31              | (1), (2), (3) |
| G 349.7+0.2 | 11    | 3.0 ± 0.4 | 4.1^2       | 0.49       | 8.4            | (4), (5), (3) |
| 3C 391 | 7.2           | 7.5 ± 1.5 | 4.5         | 0.49       | 9.3            | (6), (2), (3) |
| W 28  | 1.8           | 13.1 ± 2.6 | 1.1^**      | 3.6        | 0.30           | (7), (8), (3) |
| W 44  | 2.8           | 13.5 ± 1.5 | 1.5^**      | 5.4        | 0.28           | (1), (2), (3) |
| G 298.6+0.0 | 10   | 15 ± 2    | 0.059       | 0.44       | 0.14           | this work, (3) |

^2Distance to the source in units of kpc.

^2In units of pc. Errors indicate the radii along the major and minor axes.

^2Absorption-corrected 0.3–10 keV flux in units of 10^{-10} erg cm^{-2} s^{-1}.

^20.1–100 GeV flux in units of 10^{-29} erg cm^{-2} s^{-1}.

^2References: (1) Claussen et al. (2010a); (2) Kawasaki et al. (2005); (3) Acero (2015); (4) Tian and Leahy (2014); (5) Yasumi et al. (2014); (6) Radhakrishnan et al. (1972); (7) Clemens (1985); (8) Rho and Borkowski (2002).

^Only ISM component was considered.

^The X-ray flux was not extracted from the entire SNR but from the brightest central region.
We selected samples with known total absorption-corrected X-ray and GeV gamma-ray fluxes. Recent studies have revealed that some of our samples have X-ray emission from recombining plasma, based on detailed analyses (Ozawa et al. 2009; Uchida et al. 2012; Sato et al. 2014). However, we concentrate on the total X-ray flux based on older results, since it permits easy comparison with other fainter sources. IC443 is one of the famous MM SNRs with GeV gamma-rays (Yamaguchi et al. 2009; Abdo et al. 2010c), but does not have a precise estimate of the total X-ray flux in literatures due to its large apparent diameters. We therefore did not choose it as our sample. We also ignored the emission from ejecta reported concerning W49B and G349.7+0.2 (Kawasaki et al. 2005; Yasumi et al. 2014), which contributes only ~10% of the total flux. GeV gamma-ray spectra of several sources have spectral breaks at around 10 GeV (e.g., Abdo et al. 2010a,b,c). To treat fainter sources equally, we used the total energy flux from the Fermi source catalog (Acero 2015). The difference between the flux of W44 placed in the catalog and that derived by Abdo et al. (2010a) is only ~20%, which is negligible for our study. We estimated the radii using the catalog of Galactic SNRs by Green (2014).

The flux ratio between 0.3–10 keV and 0.1–100 GeV, $F_X/F_G$, given in table 2 is within a range of ~0.1–30. If 3FGL J1214.0–6236 is the gamma-ray counterpart of G298.6–0.0, our target has the faintest $F_X/F_G$ ratio. Figure 3a shows the radius vs. $F_X/F_G$ of MM SNRs with GeV gamma-rays. The flux ratio shows a decline, as the radii of SNRs become larger, or SNRs grow old. The flux ratio of our target is very consistent with this trend.

It is unclear why the flux ratio becomes smaller when MM SNRs evolve. One possibility is that the X-ray luminosity decreases more rapidly due to expansion and cooling (Gehrels & Williams 1993), whereas the GeV gamma-ray luminosity does not decrease. In order to check this hypothesis, we made plots of the radius vs. 0.3–10 keV luminosity (figure 3b) or 0.1–100 GeV luminosity (figure 3c). This is consistent with our scenario: the X-ray luminosity becomes smaller when the SNRs evolve (or their radii become larger), whereas the gamma-ray luminosity is almost constant within a range of $10^{35}$–$10^{36}$ erg s$^{-1}$. This is also consistent with previous results in X-rays (Long 1983) and GeV gamma-rays (Brandt et al. 2015). The constant gamma-ray flux supports our hypothesis that the timescale for low-energy particles to escape these SNRs is long compared to the SNR evolution. This trend also implies that a part of Galactic GeV unID sources can be much evolved MM SNRs without any significant detection in the X-ray and radio bands. Note that the radio surface brightness becomes smaller when the SNR evolves (Case & Bhattacharya 1998), which makes it difficult to detect them together with large angular size. A further study of a large sample of GeV gamma-ray SNRs is needed to understand this tendency.

**Fig. 3.** (a) Radius vs. flux ratio between 0.3–10 keV (absorption-corrected, $F_X$) and 0.1–100 GeV ($F_G$) for MM SNRs with GeV gamma-ray emission. Circles and a box represent the samples from literatures and from this work, respectively, in all panels. (b) Radius vs. 0.3–10 keV luminosity. (c) Radius vs. 0.1–100 GeV luminosity.

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