A Suzaku Study of Ejecta Structure and Origin of Hard X-Ray Emission in the Supernova Remnant G 156.2+5.7

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Abstract

We report on an X-ray study of the evolved Galactic supernova remnant (SNR) G 156.2+5.7 based on six pointing observations with Suzaku. The remnant’s large extent (100’ in diameter) allows us to investigate its radial structure in the northwestern and eastern directions from the apparent center. The X-ray spectra were well fit with a two-component non-equilibrium ionization model representing the swept-up interstellar medium (ISM) and the metal-rich ejecta. We found prominent central concentrations of Si, S, and Fe from the ejecta component; the lighter elements of O, Ne, and Mg were distributed more uniformly. The temperature of the ISM component suggests a slow shock (610–960 km s⁻¹); hence, the remnant’s age is estimated to be ~7000–15000 yr, assuming its distance to be ~1.1 kpc. G 156.2+5.7 has also been thought to emit hard, non-thermal X-rays, despite being considerably older than any other such remnant. In response to a recent discovery of a background cluster of galaxies (2XMM J045637.2+522411), we carefully excluded its contribution, and reexamined the origin of the hard X-ray emission. We found that the residual hard X-ray emission is consistent with the expected level of the cosmic X-ray background. Thus, no robust evidence for non-thermal emission was obtained from G 156.2+5.7. These results are consistent with the picture of an evolved SNR.

Key words: ISM: abundances — ISM: individual (G 156.2+5.7) — ISM: supernova remnants — X-rays: ISM

1. Introduction

G 156.2+5.7 (RX 04591+5147) was initially discovered in X-ray with ROSAT (Pfeffermann et al. 1991). Its age was estimated to be ~26000 yr, based on the Sedov model; hence, it is thought to be an evolved supernova remnant (SNR). The distance is comparatively nearby (~1.1 kpc: Pfeffermann et al. 1991) and its large apparent size (~100’ in diameter) enables us to study the detailed plasma structure. While G 156.2+5.7 is one of the brightest SNRs in X-rays, its radio emission is quite faint; this is the most remarkable feature. Shortly after its discovery in X-rays, the radio continuum emission was also detected with the Effelsberg 100 m telescope (Reich et al. 1992). As they point out, the surface brightness at 1 GHz (5.8 × 10⁻²³ W m⁻² Hz⁻¹ sr⁻¹) is the lowest among all known SNRs. The radio morphology along the northwest and southeast rim shows limb brightening (Reich et al. 1992; Xu et al. 2007), which is typically seen in “barrel-shaped” SNRs (Kesteven & Caswell 1987). In contrast to its radio morphology, G 156.2+5.7 has centrally filled thermal emission in X-rays. While Lazendic and Slane (2006) lists G 156.2+5.7 as a mixed-morphology (MM) SNR for this reason, it does not fit the definition of MM SNRs in several ways: the X-ray shell is easily distinguishable, and there are neither CO clouds nor OH (1720 MHz) masers in its vicinity. A recent optical observation suggests that the distance to G 156.2+5.7 is smaller than the previously estimated one (Gerardy & Fesen 2007). Their main argument is that several bright Hα filaments correlate with nearby interstellar clouds (~0.3 kpc). However, X-ray and radio observations agree as to that G 156.2+5.7 is located at ~1–3 kpc, i.e., an evolved SNR (Pfeffermann et al. 1991; Reich et al. 1992). The distance and the age of this SNR remain open questions.

The X-ray spectrum of G 156.2+5.7 is also largely typical of an evolved SNR. Yamauchi et al. (1993) observed G 156.2+5.7 with the Ginga LAC (large-area proportional counters), and detected extended X-ray emission in the 1.2–3.0 keV energy band. Yamauchi et al. (1999) performed an additional observation with ASCA, and found that its spectrum consists of two components with different features. The soft component has several emission lines, suggesting a thin thermal origin, whereas the hard component is featureless. However, due to a lack of statistics, they were not able to decide whether the featureless hard component has a thermal origin or a non-thermal one. Katsuda et al. (2009) observed two rims (northwest and east) and the center with Suzaku. They...
found two thermal components, one of which they ascribed to interstellar material heated by the forward shock, and the other reverse-shock heated ejecta. They also detected hard X-rays observed in the northwestern rim and the center, which they concluded is likely to be non-thermal synchrotron emission. If this is the case, G 156.2+5.7 would be the oldest SNR producing non-thermal X-ray emission. However, a recent Suzaku observation discovered a cluster of galaxies (2XMM J045637.2+522411: Yamauchi et al. 2010) located in the northwestern rim. Since the surface brightness of this extended source is higher than that of the rim, we need careful consideration of its contribution to determine the true origin of the hard component.

Katsuda et al. (2009) also estimated the progenitor mass to be less than 15 \(M_\odot\) from the metal abundances of the thermal emission detected in the central portion. While no compact source has been discovered in G 156.2+5.7 (see Kaplan et al. 2006), their result suggests that its origin is a core-collapse supernova (SN) rather than a type Ia SN. More recently, Hudaverdi et al. (2010) observed the center of this remnant with XMM-Newton, and measured its metallicity. From the results, they suggested that G 156.2+5.7 is an O-rich SNR.

We performed 6 pointing observations of G 156.2+5.7 with Suzaku. The fields of view (FoV) cover three sections of the rim and three inner regions, and include those discussed in Katsuda et al. (2009). In this paper, we report on the ejecta distribution, and review the origin of the hard X-ray emission detected by Katsuda et al. (2009) along with the newly observed regions. We also discuss the age of this SNR based on these analyses.

2. Observations and Data Reduction

We summarize the six observations in Table 1. Data were taken during the Suzaku AO1 phase in 2007 and during AO4 in 2010. The observed regions are shown in figure 1. The square represents the FoV of the Suzaku XIS (X-ray Imaging Spectrometer: Koyama et al. 2007). The data were analyzed with version 6.9 of the HEASoft tools. For data reduction we used version 9 of the Suzaku Software. The calibration database (CALDB) used was what was updated in 2010 March. We used revision 2.2 of the cleaned event data, and combined the \(3 \times 3\) and \(5 \times 5\) event files. In order to exclude background flare events, we obtained good time intervals (GTIs) by including only times at which the count rates in the various detectors are less than \(+3\sigma\) of the mean count rates.

### 3. Spectral Analysis

For the following analysis, the energy range of 0.4–8.0 keV was used for XIS1 (back-illuminated CCD: BI CCD) and XIS0 and XIS3 (front-illuminated CCDs: FI CCDs), since there was no signal above 8.0 keV after background subtraction (described below). In order to generate response matrix files (RMFs) and ancillary response files (ARFs), we employed \texttt{xissimarfgen} and \texttt{xissimarfgen} (Ishisaki et al. 2007). We used XSPEC version 12.6.0 (Arnaud 1996) for all the following spectral analyses. We excluded 2XMM J045637.2+522411 and three other point-like sources identified from the XIS image (0.5–5.0 keV). The extracted regions are shown in figure 1.

#### 3.1. Background Subtraction

Since G 156.2+5.7 is a large diffuse source and its FoV is filled with SNR’s emission, it is hard to obtain the background spectra inside the FoV. We also have no background data of fields in the neighborhood of the G 156.2+5.7. For the following analysis, we used a generated non-X-ray background (NXB) spectra by employing \texttt{xisnxbgen} (Tawa et al. 2008). We also took into account the contributions of the local hot bubble (LHB) and the cosmic X-ray background (CXB) by assuming literature-based models. For the LHB,

### Table 1. Summary of the six Suzaku observations.

| Name | Obs. ID | Obs. date | RA, Dec (J2000.0) | Effective exposure |
|------|---------|-----------|-------------------|-------------------|
| NW\(_{\text{rim}}\) | 501075010 | 2007-Feb-16 | \(04^\text{h}56^\text{m}54.9^s, 52^\circ24'12.6''\) | 50.5 ks |
| Center | 501106010 | 2007-Feb-17 | \(04^\text{h}58^\text{m}54.9^s, 51^\circ44'36.1''\) | 51.2 ks |
| E\(_{\text{rim}}\) | 501074010 | 2007-Feb-18 | \(05^\text{h}03^\text{m}13.5^s, 51^\circ37'06.2''\) | 53.3 ks |
| East | 504082010 | 2010-Feb-21 | \(05^\text{h}01^\text{m}03.0^s, 51^\circ41'41.6''\) | 50.3 ks |
| NW | 504081010 | 2010-Mar-03 | \(04^\text{h}57^\text{m}42.1^s, 52^\circ04'31.1''\) | 52.9 ks |
| S\(_{\text{rim}}\) | 504080010 | 2010-Mar-04 | \(04^\text{h}59^\text{m}41.8^s, 51^\circ00'36.0''\) | 52.6 ks |

### Table 2. Surface brightnesses of hard emission in G 156.2+5.6 and two nearby observations.

| Name | \(l\) [deg] | \(b\) [deg] | Surface brightness at 2.0–10.0 keV \([10^{-11}\text{erg cm}^{-2}\text{s}^{-1}\text{deg}^{-2}]\) |
|------|-------------|-------------|----------------------------------|
| G 156.2+5.7 NW\(_{\text{rim}}\) | 155.5 | 5.8 | 1.88 \(\pm\) 0.26 |
| G 156.2+5.7 E\(_{\text{rim}}\) | 156.7 | 6.1 | 1.61 \(\pm\) 0.23 |
| G 156.2+5.7 S\(_{\text{rim}}\) | 156.8 | 5.3 | 1.56 \(\pm\) 0.22 |
| IRAS 05262+4432 BGD | 165.0 | 5.6 | 1.78 \(\pm\) 0.25 |
| SGR 0501+4516 BGD | 161.4 | 1.9 | 1.89 \(\pm\) 0.26 |
we used an APEC model (Smith et al. 2001) with solar abundances (Anders & Grevesse 1989) and an electron temperature of 0.1 keV (Miller et al. 2008). For the CXB, we employed a broken power-law model with photon indices of $\Gamma = 2.0$ ($<0.7$ keV) and $\Gamma = 1.4$ ($>0.7$ keV), as shown by Miller et al. (2008). Hereafter, we call this model the CXB model. We also reviewed the effect of the Galactic Ridge X-ray Emission (GRXE). The GRXE surface brightness at $l = 100^\circ$ and $|b| < 1^\circ$ is $\sim 1.4 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$ in the 0.7–10.0 keV band (Sugizaki et al. 2001). Since G 156.2+5.7 is located outside the FoV of Sugizaki et al. (2001) and away from the galactic plane, the contribution of the GRXE is expected to be negligible. For example, the GRXE surface brightness above 2.0 keV decreases by about one-fourth from $b = 0^\circ$ to $b \sim 9^\circ$ (Revnivtsev et al. 2006). Additionally, the average 0.7–10.0 keV band surface brightness of G 156.2+5.7 is $\sim 4.3 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$ (Yamauchi et al. 1999), which is an order of magnitude higher than the minimum Suzaku surface brightness of $\sim 3.4 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$ that we see in the S_rim observation. In both cases, we conclude that the effect of the GRXE is negligible in G 156.2+5.7.

Table 2 shows the surface brightness of the CXB and the GRXE near G 156.2+5.7 and within a few degrees using observations of IRAS 05262+4432 (narrow-line Seyfert 1: Kawaguchi et al. 2008) and SGR 0501+4516 (soft gamma repeater: Enoto et al. 2009). Since both are point-like sources, we excluded the source regions with radii 4'0, and fitted the spectra obtained from the remaining regions with the CXB model. Comparing the surface brightness of each observation, the levels of the CXB and the GRXE are uniform within the range of error. Figure 2 left shows the surface brightness distribution of the CXB component inferred from the fit to each annular region in G 156.2+5.7 (the details will be argued
hereinafter). The filled circles, open circles, crosses, and squares correspond to regions from the E_rim, East, Center, and NW, respectively. Green represents regions from the S_rim. The result suggests that the level of the CXB (and the GRXE) inside this remnant is also unchanged within the range of error.

3.2. Model Fit for the Rim Regions’ Spectra

Since the rims are mostly dominated by an interstellar medium (ISM) component (Katsuda et al. 2009), we applied a single-component VNEI (non-equilibrium ionization ver.2.0: Borkowski et al. 2001) model with TBabs (Tübingen-Boulder ISM absorption model: Wilms et al. 2000) in XSPEC for the rim spectra. In this model, it is allowed to freely vary the abundances relative to the solar values (Anders & Grevesse 1989) of N, O, Ne, Mg, Si, S, and Fe, and the abundance of Ni is linked to that of Fe. The abundances of the other elements were fixed at their solar values. Other parameters were all free: the electron temperature, $kT_e$, the ionization timescale, $\tau$ (a product of the electron density and the elapsed time after the shock heating), and the emission measure ($EM = \int n_e n_H dI$, where $n_e$ and $n_H$ are the number densities of hydrogen and electrons, and $dI$ is the plasma depth). We also allowed a column density, $N_H$, to vary freely. Katsuda et al. (2009) applied the CXB model plus an additional power-law component to the hard X-ray tail. They used the same value of $N_H$ for the CXB as that of other components. In our analysis, it was fixed at $3.6 \times 10^{21} \text{cm}^{-2}$, calculated by $nh$ FTOOL\(^1\) and separated from the $N_H$ of G 156.2+5.7. The additional power-law component was not applied to our analysis unless the CXB surface brightness exceeded the literature value.

Katsuda et al. (2009) found excess emissions over the CXB above 3 keV in the NW_rim, and argued that the observed excess originates from a non-thermal emission from G 156.2+5.7. In their analysis, they excluded a region within the 1/2 radius from the position, where 2XMM J045637.2+522411 is located. Although Yamauchi et al. (2010) estimated the extension of the X-ray emission from 2XMM J045637.2+522411 to be at least $\sim 50''$ (the surface brightness within it is $\sim 2.64 \times 10^{-10} \text{erg cm}^{-2} \text{s}^{-1} \text{deg}^{-2}$ in the 2.0–10.0 keV band) based on the XMM-Newton data, we noticed that its extent might be larger. The left and right panels of figure 3 show a full-band (0.3–8.0 keV) image and a hard-band (2.0–8.0 keV) one, respectively. In figure 3, we show the small circular region within a radius of 1/2, as used by Katsuda et al. (2009). We find that the X-ray emission from the cluster extends beyond this circle, even in the hard band. Figure 4 shows a radial profile from the center of 2XMM J045637.2+522411 in the 2.0–8.0 keV band. The dotted vertical line corresponds to a radius of 1/2. Figure 4 shows that the surface brightness decreases to half at a radius of $\sim 3''$. To rule out possible contamination from 2XMM J045637.2+522411, we therefore excluded a circular region within a radius of 4/0, as shown by the white large circle in figure 3. The fitting result after excluding this larger region is shown in figure 5. The best-fit parameters are given in table 3.

The surface brightness of the hard component in the NW_rim spectrum fitted with the single-component VNEI model.

NW_rim was calculated to be $1.88 \times 10^{-11} \text{erg cm}^{-2} \text{s}^{-1} \text{deg}^{-2}$ (2.0–10.0 keV, table 3). On the other hand, the CXB surface brightness is estimated to be $(1.57 \pm 0.32) \times 10^{-11} \text{erg cm}^{-2} \text{s}^{-1} \text{deg}^{-2}$ based on blank-sky observations with the XIS (Tawa 2008). In their analysis, a spatial

\(^{1}\) (http://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl).
fluctuation of 14% (1σ) is considered for the XIS FoV (Tawa et al. 2008). Accordingly, the surface brightness of the hard component in the NW rim (and also E_rim and S_rim) is within the uncertainty of the CXB surface brightness. We conclude that no additional power-law component is required for our fit.

3.3. Model Fit for the Inner Regions’ Spectra

We also applied the single-component VNEI model to each inner region. However, this model was inadequate to fit the data due to its simplicity. As previously shown by Katsuda et al. (2009), the thermal emission from the interior of G 156.2+5.7 consists of two components with different origins: a high-temperature ejecta component and a low-temperature ISM component. Thus, we applied a two-component VNEI model to the spectra obtained from Center, East, and NW. In this model, we fixed the ISM abundances to the average values based on the fitting results of rim observations (see table 3). The average abundances of the ISM component are set in the following ways: N = 0.23, O = 0.24, Ne = 0.45, Mg = 0.39, Si (= S) = 0.50, and Fe (= Ni) = 0.38. We fixed the other abundances at the solar values. We also set $kT_e$ to be 0.45 keV, which is an average electron temperature for the rim regions of G 156.2+5.7. It is allowed to vary the values of $\tau$ and $EM$. Meanwhile, in the ejecta component, the abundances of O, Ne, Mg, Si, S, and Fe were free, while we set the abundances of C and N equal to O, and that of Ni equal to Fe. All other abundances were fixed at their solar values. The other free parameters were $kT_e$, $\tau$, $EM$, and the column density, $N_H$.

We note that the temperature of the low-$kT$ component may be higher than that of the rim because the line-of-sight ISM component includes the ambient medium shocked earlier in the evolution of the remnant when the shock velocity was higher. In general, higher ISM temperatures will increase the line emission from species, such as Si and S, which may affect the ejecta abundance measurement. Since it is impossible to measure the real average temperature of the ISM component, we examined how the metal abundances change by increasing the ISM temperature from 0.45 keV to 2.0 keV. As a result, we concluded that the ISM temperature hardly affected the ejecta abundances within the range of the error. We thus fixed the ISM temperature for the inner regions’ spectra at 0.45 keV.

4. Discussion

4.1. Ejecta Structure

Figure 6 shows band images of O VII, O VIII, Ne IX, Mg XI, Si XIII, and S XV using all of the Suzaku data. In figure 6, Si and S distributions both appear to be centrally concentrated, while those of O VII and O VIII show a clear limb brightening, which suggests that the observed heavy elements originate from the ejecta. Furthermore, figure 6 suggests that the distribution

\[
\begin{array}{|c|c|c|}
\hline
\text{Component} & \text{Parameter} & \text{Value} \\
\hline
\text{CXB model} & \text{absorption} & \text{N}_H \ [10^{21} \text{ cm}^{-2}] \ldots \ 2.3 \pm 0.1 \ 2.0 \pm 0.1 \ 3.1 \pm 0.1 \\
& \text{broken power-law} & kT_e \ [\text{keV}] \ldots \ 0.45 \pm 0.01 \ 0.49 \pm 0.01 \ 0.41 \pm 0.01 \\
& & \log(\tau \ [\text{s cm}^{-3}]) \ldots \ 10.64 \pm 0.02 \ 10.54^{+0.01}_{-0.02} \ 10.80^{+0.03}_{-0.02} \\
& & \text{abundances} \ldots \ 0.12 \pm 0.01 \ 0.15 \pm 0.01 \ 0.50 \pm 0.01 \\
& & \text{surface brightness}^* \ 1.88 \times 10^{-11} \ 1.61 \times 10^{-11} \ 1.56 \times 10^{-11} \\
\hline
\text{LHB model} & \text{APEC} & kT_e \ [\text{keV}] \ldots \ 0.1 \ (\text{fixed}) \ 1 \ (\text{fixed}) \\
& & \text{abundances} \ldots \ 0.24 \pm 0.01 \ 0.22 \pm 0.01 \ 0.25 \pm 0.01 \\
& & \text{surface brightness}^* \ 3.3 \times 10^{-16} \ (\text{fixed}) \\
\hline
\text{VNEI model} & \text{absorption} & \text{N}_H \ [10^{21} \text{ cm}^{-2}] \ldots \ 2.0 \pm 0.1 \ 2.0 \pm 0.1 \ 3.1 \pm 0.1 \\
& & kT_e \ [\text{keV}] \ldots \ 0.45 \pm 0.01 \ 0.49 \pm 0.01 \ 0.41 \pm 0.01 \\
& & \log(\tau \ [\text{s cm}^{-3}]) \ldots \ 10.64 \pm 0.02 \ 10.54^{+0.01}_{-0.02} \ 10.80^{+0.03}_{-0.02} \\
& & \text{abundances} \ldots \ 0.12 \pm 0.01 \ 0.15 \pm 0.01 \ 0.50 \pm 0.01 \\
& & \text{surface brightness}^* \ 1.88 \times 10^{-11} \ 1.61 \times 10^{-11} \ 1.56 \times 10^{-11} \\
& & \chi^2/\text{dof} \ldots \ 1395/1245 \ 1441/1190 \ 1183/1031 \\
\hline
\end{array}
\]

* 2.0–10.0 keV surface brightness in units of erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$. Other elements are fixed at solar values. The errors are in the range of $\Delta \chi^2 < 2.7$ on one parameter.
centers of Si and S shift toward the northwest.

To examine the radial distribution of the plasma, we divided the data into annular regions, as shown in figure 1 right. As the annular center we used 04°58′54″9, 51°44′36″1 (J2000.0), the optical axis during the observation of Center. We used an annular width of 2′, consistent with the angular resolution of the XIS. In order to estimate the boundary of the ejecta-dominated region, we applied both the single-component VNEI model and the two-component VNEI one to the spectra obtained from the E_rim and NW_rim. We determined which model is preferred by using the $F$-test with a significance level of 99%. We found that the second component is required in the NW_rim only within roughly $\sim 85\%$ of the shock radius ($\sim 52′$). Figure 7 shows example spectra obtained from the annular regions 25′ away from the annular center toward the east (E-25, left) and the northwest (NW-25, right). The best-fit parameters are given in table 4. While both spectra require the two-component VNEI model, the abundances of the ejecta component are significantly different, particularly for Si and S. We also note that there is no positive evidence that G 156.2+5.7 is an O-rich SNR, as claimed by Hudaverdi et al. (2010). Their argument is that the south and east sides of their FoV are soft X-ray dominated (0.4–1.0 keV), suggesting the abundant presence of O. However, we consider...
Table 4. Spectral parameters.

| Component      | Parameter                        | Value             |
|----------------|----------------------------------|-------------------|
|                |                                  | Region E-25       |
|                |                                  | Region NW-25      |
| CXB model      | absorption                       |                   |
|                | $N_H \times 10^{21}$ cm$^{-2}$   | 3.6 (fixed)       |
|                | $\Gamma_1$                       | 2.0 (fixed)       |
|                | $E_{\text{break}}$ [keV]         | 0.7 (fixed)       |
|                | $\Gamma_2$                       | 1.4 (fixed)       |
|                | surface brightness$^a$           | $1.48 \times 10^{-11}$ |
|                |                                  | $1.74 \times 10^{-11}$ |
|                | broken power-law                 |                   |
|                | $\Gamma_1$                       | 2.0 (fixed)       |
|                | $E_{\text{break}}$ [keV]         | 0.7 (fixed)       |
|                | $\Gamma_2$                       | 1.4 (fixed)       |
|                | surface brightness$^a$           | $1.48 \times 10^{-11}$ |
|                |                                  | $1.74 \times 10^{-11}$ |
| LHB model      | $APEC$                           |                   |
|                | $kT_e$ [keV]                     | 0.1 (fixed)       |
|                | abundances                       | 1 (fixed)         |
|                | surface brightness$^a$           | $3.3 \times 10^{-16}$ (fixed) |
| VNEI model     | absorption                       |                   |
|                | $N_H \times 10^{21}$ cm$^{-2}$   | 1.8 ± 0.1         |
|                |                                  | 3.4 ± 0.1         |
|                | low-$kT_e$ component             |                   |
|                | $kT_e$ [keV]                     | 0.45 (fixed)      |
|                | $\log(\tau$ [s cm$^{-3}$])      | $11.38^{+0.08}_{-0.07}$ |
|                | $N$                              | 0.23 (fixed)      |
|                | $O$                              | 0.24 (fixed)      |
|                | $\text{Ne}$                      | 0.45 (fixed)      |
|                | $\text{Mg}$                      | 0.39 (fixed)      |
|                | $\text{Si}$                      | 0.50 (fixed)      |
|                | $\text{S}$                       | 0.50 (fixed)      |
|                | $\text{Fe} (= \text{Ni})$       | 0.38 (fixed)      |
|                | high-$kT_e$ component            |                   |
|                | $kT_e$ [keV]                     | $0.59^{+0.02}_{-0.01}$ |
|                | $\log(\tau$ [s cm$^{-3}$])      | $11.29 \pm 0.04$  |
|                | $O$                              | $1.18^{+0.22}_{-0.21}$ |
|                | $\text{Ne}$                      | $0.51 \pm 0.11$  |
|                | $\text{Mg}$                      | $0.83^{+0.13}_{-0.12}$ |
|                | $\text{Si}$                      | $0.48 \pm 0.22$  |
|                | $\text{S}$                       | <1.5              |
|                | $\text{Fe} (= \text{Ni})$       | $1.05 \pm 0.07$  |
|                | $\chi^2$/dof                     | $379/326$         |
|                |                                  | $533/453$         |

$^a$ (see figure 7)

$^\dagger$ 2.0–10.0 keV surface brightness in units of erg cm$^{-2}$ s$^{-1}$ deg$^{-2}$. Other elements are fixed at solar values. The errors are in the range of $\Delta \chi^2 < 2.7$ on one parameter.

that such excesses are mainly due to the contribution of the low-temperature ISM component.

Figure 8 shows radial profiles of the emission measure for various metals (O, Ne, Mg, Si, S, and Fe) in the ejecta. We found prominent central concentrations for Si, S, and Fe, while the lighter elements (O, Ne, and Mg) are distributed more uniformly. The emission measure of Si peaks at $\sim 10\prime$ from the annular center and the overall distribution is quite similar to that of S. The coexistence of Si with S is consistent with a theoretical picture that they are mainly produced in the static O-burning layer during the stellar evolution, and incomplete Si-burning layer during the SN explosion. Similar shifts have been observed in other evolved SNRs, for example, the Cygnus Loop (Uchida et al. 2009). If such inhomogeneities are real, one of the possible causes is an asymmetric explosion of a progenitor star. While many SN models have been proposed in recent decades, a model invoking delayed explosion caused by neutrino heating is worth considering in the context of these data. For example, Marek and Janka (2009) simulated an SN explosion of $15 M_\odot$ caused by the SASI-aided core-collapse (SASI: standing accretion shock instability). They expect that the heavy elements, such as Si and Fe, are ejected in one direction, while the lighter elements, such as O, Ne, and Mg, are ejected in all directions. However, since our FoV is limited, we cannot determine the precise distribution center of each ejected element. Also, the annular center does not necessarily correspond to the explosion center. It should be carefully studied whether
the origin of such an inhomogeneous distribution is actually the result of an asymmetric SN explosion or not.

4.2. Origin of Hard X-Ray Emission

As shown in subsection 3.2, we found no robust evidence for non-thermal emission in the NW rim when we excluded the region contaminated by the cluster 2XMMJ045637.2+522411. The consistency between the CXB surface brightness measured in the NW rim and those of other observations’ measurements (see table 2) as well as those found in the literature strengthens the conclusion that there is no non-thermal emission from the NW rim.

We next consider the spatial fluctuation of the hard X-ray surface brightness using all of the spectra obtained from the annular regions described above (see figure 2). In figure 2 left, there is no correlation between the radio synchrotron and
the hard X-ray emission, contrary to the prediction by Katsuda et al. (2009). The hard X-ray distribution does not have a bilaterally symmetric morphology, like some non-thermal SNRs (e.g., SN1006: Koyama et al. 1995). Figure 2 right shows a histogram of calculated surface brightnesses. The horizontal arrow represents the 1σ spatial fluctuation of the CXB surface brightness estimated by Tawa (2008). Surface brightnesses in almost all regions (~94%) are within the 3σ fluctuation, which suggests that the observed hard X-ray emission is dominated by the CXB. Although Katsuda et al. (2009) argued that non-thermal emission was also detected at the SNR’s center, figure 2 shows that the hard surface brightness from this region is also consistent with CXB fluctuations, as is the case in the NW rim. As a result, there is no robust evidence for non-thermal emission from this remnant.

4.3. Estimating the Age of G 156.2+5.7

As shown above, the observed hard X-ray emission is dominated by the CXB everywhere, except in the region of 4.0 around 2XMM J045637.2+522441. This fact supports the idea that G 156.2+5.7 is an evolved SNR, despite the claim of Gerardy and Fesen (2007) that it was a young nearby SNR. As explained in subsection 4.1, G 156.2+5.7 has a layered metallicity structure that is observed in other evolved SNRs (e.g., Cygnus Loop: Tsunemi et al. 2007). Such a structure suggests that the reverse shock has already reached the center of G 156.2+5.7. Furthermore, the electron temperature (~1 keV) is much lower than that in many young SNRs. All of the results support the picture of an evolved SNR. For these reasons, we prefer ~1.1 kpc (Pfeffermann et al. 1991) to ~0.3 kpc (Gerardy & Fesen 2007) for its distance, d, in the following analysis.

Assuming thermal equilibrium between electrons and protons, we find that the forward shock velocity, $v_s$, is estimated to be $v_s \approx 614 \left(\frac{m_T}{m_p}\right)^{0.5} \frac{\text{km s}^{-1}}{\text{keV}}$. However, Ghavamian et al. (2001) calculated an initial equilibration of only 50% for shock speeds of ~600 km s$^{-1}$. In such a non-equilibrium case, the electron temperature, $kT_e$, and the proton temperature, $kT_p$, are expressed in the following equations (Ghavamian et al. 2001):

$$kT_p \approx \frac{3}{2} \left[ \frac{m_e}{m_p} f_{eq} + (2 - f_{eq}) m_p \right] v_s^2,$$

(1)

$$kT_e \approx \frac{3}{2} \left[ \frac{m_p}{m_e} f_{eq} + (2 - f_{eq}) m_e \right] v_s^2,$$

(2)

$$\frac{T_e}{T_p} \approx \frac{f_{eq}}{2 - f_{eq}},$$

(3)

where $m_p$ and $m_e$ are the proton and electron masses, respectively. If the initial electron–proton equilibration, $f_{eq}$, is 0.5, $v_s$ is $960 \left(\frac{kT_e}{0.45 \text{keV}}\right)^{0.5} \text{km s}^{-1}$, which gives an upper limit of $v_s$.

On the other hand, the ambient densities ($n_0$) in the NW rim and the E rim are $n_0_{NW} = 0.084 (d/1.1 \text{kpc})^{-1} \text{cm}^{-3}$ and $n_0_{E} = 0.091 (d/1.1 \text{kpc})^{-1} \text{cm}^{-3}$, respectively, by fitting their emission measure profiles with a Sedov model (Katsuda et al. 2009). Due to a lack of statistics, it is hard to estimate the ambient density in the S rim in the same way. We therefore consider the average value of two calculated $n_0$ to be a global ambient density of G 156.2+5.7; hence, $n_0 = 0.088 (d/1.1 \text{kpc})^{-1} \text{cm}^{-3}$. Applying a simple Sedov analysis, the age $t_4 = t/10^4 \text{yr}$ is as follows:

$$t_4 \approx 1.5 \left(\frac{v_s}{614 \text{km s}^{-1}}\right)^{-5/3} \left(\frac{E_0}{10^{51} \text{erg}}\right)^{1/3} \left(\frac{n_0}{0.088 \text{cm}^{-3}}\right)^{-1/3},$$

(4)

for the thermal equilibrium case, and

$$t_4 \approx 0.7 \left(\frac{v_s}{960 \text{km s}^{-1}}\right)^{-5/3} \left(\frac{E_0}{10^{51} \text{erg}}\right)^{1/3} \left(\frac{n_0}{0.088 \text{cm}^{-3}}\right)^{-1/3},$$

(5)

for the non-equilibrium case. Here, $E_0$ is the explosion energy.

As a result, we prefer the estimate from the ASCA observation (15000 yr: Yamauchi et al. 1999) to that from the ROSAT observation (26000 yr: Pfeffermann et al. 1991). In any case, G 156.2+5.7 is not a young SNR such as Gerardy and Fesen (2007) claimed. While Katsuda et al. (2009) pointed out that non-thermal X-ray emission would be detectable even from such an evolved SNR if the flux ratio of non-thermal to thermal emission is higher than that in the typical evolved SNR, it is more reasonable to conclude that G 156.2+5.7 is, itself, the typical evolved SNR, since CXB exceeds that of any X-ray synchrotron component.

5. Summary

We performed a set of 6 pointing observations of G 156.2+5.7 with Suzaku. The spectra were well-fitted with two-component or single-component VNEI (with CXB and LHB) models for the inner regions and rim regions, respectively. Our results are consistent with the conclusion of Katsuda et al. (2009), that these components represent reverse shock-heated ejecta and forward shock-heated ISM, respectively.

From the ejecta component, we found prominent central concentrations of Si, S, and Fe, while the lighter elements (O, Ne, and Mg) are distributed more uniformly. Such distributions reflect a layered-metallicity structure of the progenitor star.

A single-component VNEI model provided an acceptable fit for all of the rim regions; no additional power-law component was required for our fit. We found no robust evidence for the non-thermal emission in the NW rim when we excluded the region contaminated by the cluster of galaxies, 2XMM J045637.2+522441. Accordingly, we conclude that the hard X-ray emission in G 156.2+5.7 is sufficiently explained as CXB emission.

The estimated forward shock velocity is relatively slow compared with young SNRs: $v_s \approx 614-960 \left(\frac{kT_e}{0.45 \text{keV}}\right)^{0.5} \text{km s}^{-1}$. We estimated its age to be 7000–15000 (d/1.1 kpc)$^{-1}$ yr; therefore, G 156.2+5.7 is not a young, but an evolved SNR.

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