The nature of a cosmic-ray accelerator CTB37B Observed
with Suzaku and Chandra

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Abstract
We report the observation of a young supernova remnant (SNR) CTB37B with Suzaku and Chandra from which TeV γ-rays are detected by H.E.S.S. Cherenkov telescope. A Suzaku observation for 80 ksec detected a clear image of diffuse emission and high quality spectra. The spectra revealed that the diffuse emission composes of thermal and non-thermal components. The thermal component can be represented by an NEI model with a temperature, an electron density and an age of 0.9 keV, 0.4 cm$^{-3}$ and 740 yr, respectively. The low electron density, together with a low abundance of Mg and Si (<0.6$Z_{⊙}$), suggests that the explosion of CTB37B occurred in a cavity created by other preceding SNR(s). The non-thermal component was found from the south region of CTB37B. The photon index of 1.5 suggests efficient cosmic-ray acceleration. Using flux ratio between X-ray and TeV γ-ray and the assumption that the TeV γ-ray emission is powered through Inverse Compton scattering (IC), we derived that the magnetic field is $B ≃ 7.5 \mu G$, and the lower limit of the maximum energy of electrons is $\sim 173 \text{ TeV}$ with $B$ and the roll-off energy obtained by
spectrum fit. On the other hand, Aharonian et al. (2008) discovered a bright point source located near the shell of CTB37B by Chandra observation. Comparing the Suzaku and Chandra data, we found the possible variability of the point source.

Key words: acceleration of particles — ISM: individual (CTB37B) — ISM: supernova remnants — X-rays: ISM

1. Introduction

Supernova Remnants (SNRs) are one of the most promising acceleration sites of cosmic rays. In fact, ASCA detected synchrotron X-ray emission from the shell of SN 1006, which unambiguously indicates the acceleration of electrons up to $\sim 100$ TeV (Koyama et al. 1995). Following this discovery, the synchrotron X-ray emission has been discovered from a shell of a few more SNRs, such as RX J1713.7–3946 (Koyama et al. 1997) and RCW 86 (Bamba et al. 2000). On the other hand, TeV $\gamma$-rays have also been detected from some non-thermal shell-type SNRs. The radiation of TeV $\gamma$-ray is explained by either (1) Inverse-Compton scattering (IC) of cosmic microwave background photons by the same high energy electron giving rise to the X-ray synchrotron emission or (2) the decay of neutral pions that are generated by collisions between high energy protons and dense interstellar matter. The ratio of fluxes between the TeV $\gamma$-ray and the X-ray provides the magnetic field intensity as long as one assumes that the TeV $\gamma$-ray is produced through the synchrotron IC mechanism. Utilizing this characteristic, Matsumoto et al. (2007) found that the TeV $\gamma$-ray from the SNR HESS J1616$-$386 is likely the result of the proton acceleration, because the non-detection of X-ray using the Suzaku XIS provides much weaker magnetic field than the interstellar average.

Although the evidence of particle acceleration has accumulated rapidly, our knowledge is still limited on what sort of conditions are necessary for SNRs to accelerate particles. A breakthrough may be brought about by searching for thermal emission systematically from SNRs from which the TeV $\gamma$-ray emission is already detected, since the thermal emission provides us with a lot of information on the environment such as temperature, density, and age of the plasma.

CTB37B locates at $(l,b) = (348.7^\circ, +0.3^\circ)$ with a distance of $10.2 \pm 3.5$ kpc (Caswell et al. 1975). This region is one of the most active regions in our galaxy where star burst activities, a number of shell structures probably associated with recent SNRs (Kassim et al. 1991), and OH maser sources (Frail et al. 1996) are detected in radio band. TeV $\gamma$-ray emission is also detected by the H.E.S.S. observation (Aharonian et al. 2007). In spite of the evidence of the high activities in other wave bands, X-ray observations have been relatively poor. Only ASCA (Tanaka et al. 1994) has detected a part of CTB37B at the edge of the field of view of the Gas Imaging Spectrometer (GIS) (Ohashi et al. 1996; Makishima et al. 1996) in the course of the galactic plane survey (Sugizaki et al. 2001; Yamauchi et al. 2008). Although the statistics are limited and the response of the GIS is not qualified at the pointing position of CTB37B, our fit of a power law to the GIS spectrum results in a steep photon
index of $\sim 3.7$, whereas fit of an optically thin thermal plasma model requires a high temperature of $\sim 2.1$ keV. These results strongly suggest that the X-ray spectrum is a mixture of a non-thermal power law and an optically thin thermal plasma emission. In addition, Aharonian et al. (2008) discovered a bright point source located near the shell of CTB37B and diffuse emission by Chandra, although the determination accuracy of physical parameters are meager because of short exposure time.

In order to take an image and high quality spectrum of CTB37B, we have carried out an observation of CTB37B with Suzaku. In addition we used Chandra archive data to comprehend the spatial structure and compare to the data obtained with Suzaku. In § 2, we present the observation log and data reduction method. Image analysis is presented in § 3. Spectrum analysis and timing analysis are shown in § 4 and § 5, respectively. We have really detected both the thermal and non-thermal power-law components from CTB37B. Discussions are made in § 6. We summarize our results in § 7.

2. Observation and Data Reduction

2.1. Suzaku observation

CTB37B was observed with Suzaku (Mitsuda et al. 2007) during 2006 August 27–29. The nominal pointing position was (RA, Dec) = (17$^h$13$^m$57$^s$, −38°12′15″, J2000). Suzaku is equipped with two kinds of X-ray detectors; one is the Hard X-ray Detector (HXD; Takahashi et al. 2007; Kokubun et al. 2007), which is a non-imaging type detector and is sensitive in the 10-600 keV band. The other is the X-ray Imaging Spectrometer (XIS; Koyama et al. 2007), which is an X-ray CCD camera mounted on the focal plane of the X-Ray Telescope (XRT; Serlemitsos et al. 2007). In total, there are four modules of the XIS, three of which are Front-Illuminated (FI) CCDs, which are hereafter referred to as XIS-0, 2, and 3, and the other one is a Back-Illuminated (BI) CCD, which is referred to as XIS-1. We concentrate on the XIS data in this paper because the HXD has no imaging capability and hence there remains a large systematic error in estimating the flux from CTB37B.

The XIS was operated in the normal full-frame clocking mode with neither burst nor window options and SCI-off. The editing mode was $3 \times 3$ in low and medium data rates and $5 \times 5$ in high and super-high data rates. In analysis, we employed the data processed with the revision 1.2 pipeline software, and used the HEADAS software (version 6.2) and XSPEC (version 11.3.2) for the data reduction and spectral analysis, respectively. We applied the charge-transfer inefficiency (CTI) correction by ourselves with the xispi software and CTI parameters of 2006–08–23. After the screening of the data, the effective exposure time of 80 ksec in total. The response matrix files (RMF) and ancillary response files (ARF) were made using xisrmfgen and xissimarfgen (Ishisaki et al. 2007) version 2007–09–22 under the assumption that the emissions are from point source.

2.2. Chandra observation

Chandra observation was performed on the 2$^{th}$ February 2007 with the Advanced CCD Imaging Spectrometer (ACIS). Chips I0, I1, I2, I3 S2 and S3 were used. The data reduction and analysis were made using the Chandra Interactive Analysis of Observations (CIAO version 3.4, CALDB
version 3.3.0). The total exposure time is 26 ksec after screening the data.

3. Image Analysis

3.1. Suzaku images

Fig. 1 (a), (b) show Suzaku XIS images. The images are created by combining those from all the four XIS modules after being corrected for the telescope vignetting followed by being smoothed with a Gaussian with $\sigma = 12$ arcsec (a; in the 0.3–3.0 keV band, b; in the 3.0–10.0 keV band). A few sources are obviously detected in the field of view. Among them, the brightest one, peaking at $(l, b) \simeq (348^\circ 68, 0^\circ 37)$ both in the soft and hard bands, and another diffuse source appears in the south of the brightest one, at $(l, b) \simeq (348^\circ 63, 0^\circ 32)$ only bright in the band above 3 keV. In addition to these diffuse sources, one point source is detected at $(l, b) \simeq (348^\circ 56, 0^\circ 33)$ in the band below 3 keV. The sky position is consistent with that of the point source 1RXS J171354.4–381740 listed in the ROSAT Bright Star Catalogue (Voges et al. 1999). In order to investigate these sources separately, we defined the following photon-integration regions (see Fig. 1) for the spectral analysis. Region 1 is the green circle with a radius of 2'6 centered at the intensity peak of the brightest diffuse source. Region 2 is the blue ellipse with a size of 1'1 $\times$ 2'5 centered at the second diffuse source. Region 3 is the circle colored in magenta with a radius of 1'3. The other three regions with the same colors but with dashed lines define those collecting the background events. We set these background regions by taking into account the telescope vignetting.

3.2. Chandra images

As shown in Fig. 1, Chandra images are corrected for the telescope vignetting and smoothed with a Gaussian with $\sigma = 6$ arcsec (c) and $\sigma = 40$ arcsec (d, e). 18 sources are detected and listed the coordinates in Aharonian et al. (2008). The energy band is 0.3–10.0 keV (c), 0.3–3.0 keV (d), and 0.3–10.0 keV (e), respectively. For (d) and (e), we subtracted point sources from the images. The definition of the color circle is same as the Suzaku images. The most brightest source (defined as source#1) located at $(l, b) = (348^\circ 681, 0^\circ 371)$ and diffuse emission are detected in region 1. These components are mixed on Suzaku image. Region 2 is more bright than region 1 in the band above 3 keV that is consistent with Suzaku result. In region 3, there is the second bright source (defined as source#2, which is 1RXS J171354.4–381740) located at $(l, b) = (348^\circ 548, 0^\circ 322)$, and no diffuse emission were detected in 0.3–3.0 keV and 3.0–10.0 keV band. Table.1 shows the background subtracted counts of source#1 and the diffuse emission comprehended region 1 and region 2. Other point sources are mixed in regions on Suzaku image, although these are able to ignore because the luminosity is week and there are in the background region same as the source region.

3.3. Correlation with other energy band

Fig. 2 shows brightness contours of radio at 1.4 GHz and of TeV $\gamma$-ray with H.E.S.S. in blue and green, the peak of TeV $\gamma$-ray emission in green cross (Aharonian et al. 2008), and source#1 and
Fig. 1. Images of CTB37B with galactic coordinates. Suzaku image in the 0.3–3.0 keV band (a) and in the 3.0–10.0 keV band (b) being smoothed with a Gaussian with $\sigma = 12$ arcsec. (c) is Chandra image in the 0.3–10.0 keV band being smoothed with a Gaussian with $\sigma = 6$ arcsec. Chandra image in the 0.3–3.0 keV band (d) and in the 3.0–10.0 keV band (e) except point sources being smoothed with a Gaussian with $\sigma = 40$ arcsec. Solid circles in green, blue, and magenta are the integration region of source photons which are named as region 1 through 3 in this order. Region 1 is a circle with a radius of 2'.6, region 2 is an ellipse with a size of 1'1 \times 2'.5, and region 3 is a circle with a radius of 1'3. The dashed regions are corresponding background-integration regions.
#2 in red boxes, respectively, overlaid on the gray scale image of the Suzaku in the 0.3–10.0 keV band.

### Table 1. Counts of source#1 and diffuse emission of Chandra data.

<table>
<thead>
<tr>
<th>Region</th>
<th>Energy band</th>
<th>Point source counts</th>
<th>Diffuse emission counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>region 1</td>
<td>0.3–3.0 keV</td>
<td>662</td>
<td>813</td>
</tr>
<tr>
<td></td>
<td>3.0–10.0 keV</td>
<td>589</td>
<td>158</td>
</tr>
<tr>
<td></td>
<td>total</td>
<td>1251</td>
<td>971</td>
</tr>
<tr>
<td>region 2</td>
<td>0.3–3.0 keV</td>
<td>—</td>
<td>106</td>
</tr>
<tr>
<td></td>
<td>3.0–10.0 keV</td>
<td>—</td>
<td>231</td>
</tr>
<tr>
<td></td>
<td>total</td>
<td>—</td>
<td>337</td>
</tr>
</tbody>
</table>

Fig. 2. Gray scale Suzaku X-ray image with radio and TeV $\gamma$-ray contours (blue and green, respectively) overlaid. Red boxes are source#1 and #2, and green cross is the center of TeV $\gamma$-ray emission.

The radio image is taken from the NRAO VLA Sky Survey (NVSS) database\(^1\) (Condon et al. 1998). The X-ray emission well conforms to the shell in radio. Particularly, region 2 connect to the most southern radio sub-peak smoothly, and week brightness in radio. On the other hand, the peak of TeV $\gamma$-ray emission and source#1 are separated, and the size of the TeV source is consistent with the radius of the radio shell of $\sim 4^\prime\!5$ (from Aharonian et al. (2008)).

## 4. Spectral Analysis

In this section, we present results of spectral analysis of the three regions described above. We adopt the metal composition of Anders & Grevesse (1989) as the solar abundance. Spectral fits except for region 3 are always carried out in the 1.0–10.0 keV band, because nearly no X-ray was detected below $\sim 1$ keV due to strong absorption interstellar absorption. The parameters of diffuse emissions

\(^1\) http://www.cv.nrao.edu/nvss/
are estimated by the spectrum of Suzaku because of high quality statistics.

4.1. Region 1

First of all, we attempted to fit the Chandra spectrum of source#1 taken with a radius of $\sim 3''$ with a power-law model undergoing photoelectric absorption (“phabs” model in XSPEC) shown in Fig. 3 (a). The best-fit parameters are the photon index of $3.2^{+0.4}_{-0.3}$, the intrinsic flux between $2.0-10.0$ keV of $1.8 \pm 0.2 \times 10^{-12}$ ergs cm$^{-2}$s$^{-1}$ and $N_{\text{H}}$ of $4.0 \pm 0.6 \times 10^{22}$ cm$^2$, respectively. These parameters are consistent with the result of Aharonian et al. (2008). Fig. 3 (b) is the background-subtracted spectrum of Suzaku region 1. The black and red crosses represent the data points from the sum of the FI CCDs and the BI CCD, respectively. The emission from source#1 was comprehended in region 1 spectrum represented with power-law model as noted above. On the other hand, K$\alpha$ emission lines from He-like Mg, Si, S and a K$\beta$ emission line from He-like Si are detected that means spectrum composes thermal emission, whereas no Fe emission line is detected. Since we detected the emission lines from highly ionized elements, we attempted to fit a non-equilibrium collisional plasma model (“vnei” model in XSPEC, Borkowski et al. (2001), Hamilton et al. (1983), Borkowski et al. (1994) and Liedahl et al. (1995)) with absorption to the thermal component. In the fitting, we set abundances of Mg, Si, and S free to vary because we detected the emission lines from these elements. The best-fit temperature and the ionization parameter of the “vnei” component are $kT = 0.89^{+0.22}_{-0.17}$ keV and $n_e t [\text{cm}^{-3}\text{s}] = 3.5^{+13}_{-1.1} \times 10^{10}$, respectively. On the other hand, the photon index of the power-law model is $\Gamma = 3.0 \pm 0.2$ and the intrinsic flux is $3.3^{+0.3}_{-0.4} \times 10^{-12}$ ergs cm$^{-2}$s$^{-1}$. The reduced $\chi^2$ of 1.06 implies that the fit is acceptable at the 90% confidence level. The best-fit parameters are summarized in Table 2.

![Fig. 3. The spectra of region 1 (a) Chandra source#1 spectrum with a power-law model, (b) Suzaku spectrum with thermal model (VNEI) and power-law model.](image)
### Table 2. Best-fit parameters of the region 1 spectra

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Chandra source#1</th>
<th>Suzaku</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power Law</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photon Index</td>
<td>$3.2^{+0.4}_{-0.3}$</td>
<td>$3.0 \pm 0.2$</td>
</tr>
<tr>
<td>Intrinsic Flux a</td>
<td>$1.8 \pm 0.2$</td>
<td>$3.3^{+0.3}_{-0.4}$</td>
</tr>
<tr>
<td><strong>VNEI</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature [keV]</td>
<td>…</td>
<td>$0.89^{+0.21}_{-0.17}$</td>
</tr>
<tr>
<td>abundance b Mg</td>
<td>…</td>
<td>$0.61^{+0.31}_{-0.19}$</td>
</tr>
<tr>
<td>Si</td>
<td>…</td>
<td>$0.40^{+0.21}_{-0.14}$</td>
</tr>
<tr>
<td>S</td>
<td>…</td>
<td>$1.0^{+0.58}_{-0.63}$</td>
</tr>
<tr>
<td>$n_{e}t$ c</td>
<td>…</td>
<td>$3.5^{+1.3}_{-1.1}$</td>
</tr>
<tr>
<td>E.M. d</td>
<td>…</td>
<td>$2.1^{+1.6}_{-0.96}$</td>
</tr>
<tr>
<td>phabs $N_{II}$ e</td>
<td>4.0 ($\pm 0.6$)</td>
<td>$3.6^{+0.4}_{-0.2}$</td>
</tr>
<tr>
<td>$\chi^{2}$/d.o.f</td>
<td>14.6/18</td>
<td>176.1/166</td>
</tr>
</tbody>
</table>

\*a Flux in the 2.0–10.0 keV band in the unit of $10^{-14}$ ergs cm$^{-2}$ s$^{-1}$.

\*b Abundance ratio relative to the solar value (Anders & Grevesse, 1989).

\*c Ionization time–scale in the unit of $10^{10}$ s cm$^{-3}$, where $n_{e}t$ and $t$ are the electron density and age of the plasma.

\*d Emission measure $E.M. = \int n_{e}n_{III} dV \approx n_{e}^{2}V$ in the unit of $10^{56}$ cm$^{-3}$, where $n_{e}$ and $V$ are the electron density and the plasma volume.

\*e Absorption column in the unit of $10^{22}$ cm$^{-2}$.

#### 4.2. Region 2

The Suzaku spectrum of region 2 together with best-fit model and residual is shown in Fig. 4. Although their basic features such as He-like Si Kα emission line and no apparent sign of Fe emission line are common with region 1, the spectra of region 2 are statistically poorer than those of region 1. In fitting the region 2 spectra, we thus first tried a “vnei + power-law (1) + power-law (2)” model, which power-law (1) was assumed the contamination of source#1 and power-law (2) means the brightness of high energy band image (Fig. 1). The temperature, the abundances of Mg, Si, and S, the ionization parameter and the photon index of power-law (1) being fixed at the best-fit values obtained in the region 1 fit (Fig. 3b). The flux between 2.0–10.0 keV of power-law (1) is fixed of $3.3 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ because the contamination of the point source located in region 1 is $\sim 1\%$ on the assumption that the non-thermal component of region 1 was contributed from source#1. The hydrogen column density, the normalization of the vnei model, and the parameters of power-law (2) are set free to vary. The photon index of power-law (2) results in $\Gamma = 1.5 \pm 0.4$ with the reduced $\chi^{2}$ of 0.36. The result of the fit is shown in Fig. 4, and the best-fit parameters are summarized in Table 3. It is remarkable that the X-ray photon index $\Gamma = 1.5$ is consistent with the standard radio energy index of non-thermal SNRs $\alpha = 0.5$. 

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Fig. 4. The XIS spectrum of region 2 with the same vnei + power-law model applied for region 1 (Fig. 3(b)) and another power-law (2) model. The normalization of VNEI model and the parameters of power-law (2) are set free to vary.

Secondary, we replaced the power-law (2) component by an “srcut” model, which simulates a synchrotron spectrum from an exponentially cut off power-law distribution of electrons in a homogeneous magnetic field (Reynolds 1998; Reynolds & Keohane 1999). According to the Green’s catalogue\(^2\), the radio spectral index ($\alpha$) is 0.3 with a flux at 1 GHz of 26 Jy. This small index, however, is probably due to contamination of thermal emission. We thus fixed $\alpha$ at 0.5, which is the typical value of the SNRs in the radio band, and set the flux at 1 GHz free to vary. The resultant parameters of the “vnei” component are similar to those from the “vnei + power-law (1) + power-law (2)” fit. The lower limit of the roll-off energy is obtained to be 14.8 keV. We confirmed that the roll-off energy does not change drastically if we varied $\alpha$ in the range 0.3–0.7. The reduced $\chi^2$ is nearly the same as that of the power-law fit. As a matter of fact, as shown in Table 3, the best-fit roll-over energy becomes as high as $> 15$ keV, indicating the spectrum from radio to X-ray bands connect smoothly with no break point between these energy bands.

4.3 Region 3

Fig. 5 shows the background-subtracted spectra of region 3.

As indicated by the images in Fig. 1 (a), X-ray flux is detected only below $\sim 3$ keV. Since the absorption is apparently weak and there is Fe-L hump in the 0.7-0.9 keV band, this source seems to be a foreground point source, probably an active star. We thus adopted the model composed of a thin thermal collisional equilibrium plasma emission model (“mekal” model in XSPEC, Mewe et al. (1985), Mewe et al. (1986), Kaasstra, J.S. (1992) and Liedahl et al. (1995)) multiplied by photoelectric absorption, and fitted this model to the spectra in the 0.5–2.0 keV band. The result of the fit is shown in Fig. 5, and the best-fit parameters are listed in Table 4. Note that the fit residuals exhibit different behavior in the 0.7–1.0 keV band between the FI and BI CCDs. This is probably because the response

\(^2\) http://www.mrao.cam.ac.uk/surveys/snrs/
<table>
<thead>
<tr>
<th>Parameters</th>
<th>VNEI + Power law + Power law</th>
<th>VNEI + Power law + srcut</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VNEI</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E.M. (^a)</td>
<td>0.23^{+0.18}_{-0.15}</td>
<td>0.23^{+0.14}_{-0.15}</td>
</tr>
<tr>
<td><strong>Power Law (2)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photon Index</td>
<td>1.5 (±0.4)</td>
<td>⋯</td>
</tr>
<tr>
<td>Intrinsic Flux (^b)</td>
<td>0.78^{+0.07}_{-0.08}</td>
<td>⋯</td>
</tr>
<tr>
<td><strong>srcut</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>alpha</td>
<td>⋯</td>
<td>0.5 (fix)</td>
</tr>
<tr>
<td>roll-off E [keV]</td>
<td>⋯</td>
<td>&gt;14.8</td>
</tr>
<tr>
<td>Intrinsic Flux (^d)</td>
<td>⋯</td>
<td>0.78</td>
</tr>
<tr>
<td>phabs (N_H) (^c)</td>
<td>3.5^{+0.5}_{-0.7}</td>
<td>3.5^{+0.5}_{-0.7}</td>
</tr>
<tr>
<td>(\chi^2/d.o.f)</td>
<td>17.5/48</td>
<td>17.5/48</td>
</tr>
</tbody>
</table>

\(^a\) Emission measure \(E.M. = \int n_e n_H \, dV \simeq n_e^2 V\) in the unit of \(10^{58}\) cm\(^{-3}\), where \(n_e\) and \(V\) are the electron density and the plasma volume.

\(^b\) Flux in the 2.0–10.0 keV band in the unit of \(10^{-12}\) ergs cm\(^{-2}\) s\(^{-1}\).

\(^c\) Absorption column in the unit of \(10^{22}\) cm\(^{-2}\).

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**Fig. 5.** The XIS spectrum of region 3 with the MEKAL model.
functions of the XIS is not completely calibrated yet.

<table>
<thead>
<tr>
<th>Table 4. Best-fit parameters of the region 3 spectrum</th>
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<tbody>
<tr>
<td><strong>MEKAL</strong></td>
</tr>
<tr>
<td>Temperature [keV]</td>
</tr>
<tr>
<td>0.46$^{+0.03}_{-0.05}$</td>
</tr>
<tr>
<td>Abundance $^a$</td>
</tr>
<tr>
<td>0.20$^{+0.12}_{-0.07}$</td>
</tr>
<tr>
<td>Normalization $^b$ [cm$^{-4}$]</td>
</tr>
<tr>
<td>2.5$^{+1.4}_{-0.6}$</td>
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<td>phabs</td>
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<td>$N_{H}^c$</td>
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<td>$&lt;0.046$</td>
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<td>$\chi^2$/d.o.f</td>
</tr>
<tr>
<td>52.9/27</td>
</tr>
</tbody>
</table>

$^a$ Abundance ratio relative to the solar value (Anders & Grevesse, 1989).

$^b$ Normalization is $10^{-14} \frac{4\pi D^2}{A} \int n_e n_H dV$ where $D_A$ is the angular size distance to the source (cm), $n_e$ and $V$ are the electron density and the plasma volume.

$^c$ Absorption column in the unit of $10^{22}$ cm$^{-2}$.

5. Timing analysis

5.1. source#1

We checked the pulsation of source#1 with Chandra data. Source#1 was affected the instrumental dither effects because of the location of the chip edge. Resolving the dither effects, we made the light curve which was filtered with Good Time Interval (GTI), and research the pulsation shown in Fig. 6, although there are no significant trend.

![Fig. 6. The power spectrum of source#1 in the 0.3–10.0 keV band with the time bin size of 64 sec.](image-url)
5.2. source#2

We created a light curve of source#2 in the 0.5–2.0 keV band with Suzaku, which is shown in Fig. 7. Although we detected no drastic flare event, the light curve seems to show flickering. In fact, Kolmogorov–Smirnov test indicates the probability of no variability in the light curve is 0.0012.

6. Discussion

6.1. Thermal Component

6.1.1. Plasma parameters from the spectral analysis

We calculated the electron number density and the age of the thermal plasma of region 1 and region 2 on the basis of the best-fit parameters summarized in table 2 and 3. We assumed that the plasma distributes uniformly within a sphere with a radius of 1/4, that was estimated using Half-Width-of-Half-Maximum (HWHM) of image broadening of diffuse emission with Chandra. Assuming the distance to CTB37B of 10.2 kpc, we obtain the real radius of region 1 to be 
\[ r_{\text{reg1}} = 2.4 \times 10^{19} \text{ cm}, \]
and accordingly, its volume to be 
\[ V_{\text{reg1}} = \frac{4}{3} \pi r_{\text{reg1}}^3 = 9.2 \times 10^{57} \text{ cm}^3. \]
In the same way, from HWHM of an estimated image size of 1.9 × 0.9, the real size and volume of region 2 result in 
\[ r_{\text{reg2}} = 1.8 \times 10^{19} \text{ cm}, \]
\[ r_{\text{reg2,s}} = 8.4 \times 10^{18} \text{ cm} \text{ and } V_{\text{reg2}} = 5.3 \times 10^{57} \text{ cm}^3, \]
respectively. With the aid of the emission measures obtained from the spectral fitting, E.M. = \( \int n_e n_H dV = 2.1^{+1.6}_{-0.9} \times 10^{58} \text{ cm}^{-3} \) (region 1) and \( 2.3^{+1.8}_{-1.5} \times 10^{57} \text{ cm}^{-3} \) (region 2), respectively, thus the electron number density of region 1 and 2 are

\[ n_{e,\text{reg1}} = 1.5 (1.1 - 2.0) \text{ [cm}^{-3}\text{]} \]
and

\[ n_{e,\text{reg2}} = 0.66 (0.39 - 0.84) \text{ [cm}^{-3}\text{]} \].
where the regions in parentheses are those allowed at the 90% confidence level. These, together with
the ionization parameters of $n_{e,\text{reg1}} t = 3.5^{+13}_{-1.1} \times 10^{10}$ [cm$^{-3}$ s], the age of the plasma in region 1 is

$$t_{\text{reg1}} = 7.4 (4.4 - 35) \times 10^2 \text{ [yr]}.$$ 

CTB37B is one of the best candidates of SN393 in Chinese historical record (Stephenson & Green 2002). The plasma age calculated from the observed ionization parameter and emission measure supports this identification.

The number of electrons ($N_e = n_e V$) in region 1 and 2 are $N_{e,\text{reg1}} = 1.4 (1.0 - 1.8) \times 10^{58}$ and $N_{e,\text{reg2}} = 3.5 (2.1 - 4.7) \times 10^{57}$. As a result, the total mass included in the two regions are 12 (8.5–15)$M_\odot$ and 3.0 (1.8–4.0)$M_\odot$, respectively, and the thermal energy ($E = 3N_e k T$) are

$$E_{\text{reg1}} = 6.0 (3.9 - 8.2) \times 10^{49} \text{ [ergs]}$$
$$E_{\text{reg2}} = 1.5 (0.84 - 2.1) \times 10^{49} \text{ [ergs]}$$

under the assumption of energy equipartition between electrons and ions.

6.1.2. The environment of the CTB37B explosion

Based on the parameters of the thermal plasma obtained so far, we consider the environment where the supernova leading to the CTB37B remnant exploded. Since the abundances of Mg and Si are sub-solar ($\sim 0.6 Z_\odot$ and $\sim 0.4 Z_\odot$, respectively, from table 2), the X-ray emission undoubtedly originates from the interstellar matter swept by the supernova ejecta. In fact, the total accumulated mass in the regions 1 and 2 are as much as $\sim 15 M_\odot$ ($\S$ 5.1.1), which is probably much larger than the mass of the ejecta accumulated in the regions 1 and 2, because the radio shell is incomplete and contains only a part of the ejecta. It is, however, interesting to note that the densities of the thermal plasma are only $\sim 1.5$ cm$^3$ and $\sim 0.66$ cm$^3$ for regions 1 and 2, respectively. Assuming the strong shock, we obtain the pre-shock densities to be $\sim 0.38$ cm$^3$ and $\sim 0.17$ cm$^3$, respectively, which are remarkably low as those of interstellar matter in the galactic plane. One possible interpretation of the low density is that the supernova associated with CTB37B exploded in a cavity which is scraped out by preceding supernovae. In fact, there are a number of OH maser sources, molecular clouds (Frail et al. 1996; Reynoso & Mangum 2000), and SNRs including G348.5-0.0 and G348.5+0.1 (CTB37A) around CTB37B. This indicates that the region around CTB37B is one of the most active regions in the galactic plane. From the apparent radius of the CTB37B radio shell ($\sim 25$ pc) and the plasma age ($\sim 740$ yr) obtained by our observation, the mean velocity of the shock wave is calculated to be

$$v = 3.3 \times 10^4 (7.0 \times 10^3 - 5.6 \times 10^4) \text{ [km s}^{-1}]$$

This high average velocity is consistent with the interpretation that the shock wave has propagated in the low density cavity. Considering all these facts, we conclude that the shock wave activated by the supernova associated with CTB37B has propagated in a low density cavity created probably by old SNRs, and eventually hit a wall constructed in ISM swept up by them.
6.2. point sources

6.2.1. source#1

The best-fit parameters of Chandra source#1 is consistent with Aharonian et al. (2008). The measured hydrogen columns \(N_H\) of source#1 and CTB37B (diffuse emission) are the same, it seems that there is a physical association of these two objects. Source#1 was probably made by explosion of CTB37B. Though there is no evidence of pulsation with timing analysis of Chandra source#1 data. Moreover the large photon index of 3.2 and luminosity of \(2.2 \times 10^{34}\) ergs s\(^{-1}\) suggests that source#1 is anomalous X-ray pulsar (AXP) (Fahlman & Gregory 1981) or Central Compact Object (CCO) (Pavlov et al. 2004).

In addition, we compared the flux between non-thermal emission observed with Suzaku and source#1 obtained with Chandra. The flux ratio between Suzaku non-thermal emission and Chandra source#1 is \(\sim 2\) (table 2). On the other hand, number of photons of Chandra image above 3 keV, that energy band is dominant on Suzaku non-thermal emission (see Fig. 3), are source#1 of 589 cnt and diffuse emission except point sources of 158 cnt (table 1). The non-thermal component of Suzaku region 1 should contribute source#1 and diffuse emission, although double flux of Suzaku non-thermal component was not able to explain only from diffuse emission, that indicates source#1 has possibly variability. To reveal details, we need more information with monitoring or deep observation with high angular resolution satellite.

次に、すく non-thermal 成分と chandra source#1 の flux を比較する。table 2 から、chandra source#1 の flux は \(\sim 1.8 \times 10^{-12}\) ergs cm\(^{-2}\)s\(^{-1}\)、すく region 1 の non-thermal component の flux は \(\sim 3.3 \times 10^{-12}\) ergs cm\(^{-2}\)s\(^{-1}\)であり、すくの flux は約 2 倍大きい。しかしすくは空間分解能が大きいために、source#1 と diffuse 成分を分離することができない。そこで、すく region 1 のスペクトルで non-thermal が卓越する 3 keV 以上において (see Fig. 3)、region1 に含まれる Chandra image のカウント数えると、source#1 が 589 カウントに対し点源を取り除いた diffuse 分が 158 カウントと約 1/4 になっている (table 1)。ここからすく non-thermal component は点源からの寄与も混入していると言えるが、それでも 2 倍の flux を説明するためには diffuse 成分では足らず、source#1 は長いスケールで変動しているのではないかと考えられる。

6.2.2. source#2

From the spectrum fitting, the column density of \(< 4 \times 10^{20}\) cm\(^{-2}\) (table 4) is much smaller than that obtained from region 1 and 2. This result indicated that source#2 is really a foreground source. The best-fit plasma temperature of \(kT \simeq 0.5\) keV is reminiscent of an active star. The existence of flickering (§5.2) supports this suggestion.
6.3. Non-Thermal Component

X-ray emission from CTB37B is composed of the thermal component from the center and non-thermal component from the south as demonstrated in §3. Hence, CTB37B becomes the second SNR after RCW86 that possesses the thermal and non-thermal X-ray emissions and TeV $\gamma$-ray emission all together. In addition, CTB37B is now the fourth SNR, following RCW86, RX J1713.7–3946 and Vela Jr., from which non-thermal radiation is detected both in X-ray and TeV $\gamma$-ray bands. The fluxes of the non-thermal emission of these four non-thermal SNRs is compared in Table 5.

CTB37B has a flatter X-ray spectrum with a photon index of 1.5, which implies a harder spectrum than that of other SNRs. Since this photon index is equal to the typical radio photon index ($\alpha = 0.5$), we can connect the radio spectrum smoothly to that of X-ray, thereby the roll-off energy of region 2 results in as high as $\sim 15$ keV (Table 3). This value is higher than the other SNRs (RXJ1713; the upper limit of $\sim 9$ keV (Takahashi et al. 2008), SN1006; $\sim 0.23$ keV (Bamba et al. 2008), RCW86; $\sim 0.87$ keV (Bamba et al. 2005)). This indicate that the electron acceleration efficiency is high in region 2. We hereafter assume that the TeV $\gamma$-ray emission is powered through Inverse Compton scattering (IC). Then the characteristic energy of the synchrotron photons $\epsilon_{\text{sync}}$ is related to that of the IC photons $\epsilon_{\text{IC}}$ with the following equation (Aharonian et al. 1997).

$$\epsilon_{\text{IC}} \simeq 1.4 \left( \frac{\epsilon_{\text{sync}}}{0.1 \text{ keV}} \right) \left( \frac{B}{10 \mu \text{G}} \right)^{-1} \text{[TeV]}$$

(1)

This indicates that TeV electrons producing 0.1 keV X-rays by synchrotron (with $B = 10 \mu \text{G}$) emit 1.4 TeV gamma-rays by inverse-Compton, simultaneously. The flux ratio between synchrotron and IC emissions is represented as

$$\frac{f_{\text{IC}}}{f_{\text{sync}}} \simeq 0.1 \left( \frac{B}{10 \mu \text{G}} \right)^{-2},$$

(2)

where $f_{\text{sync}}$ is the X-ray flux and $f_{\text{IC}}$ is the $\gamma$-ray flux (Aharonian et al. 1997). With these two equations, we obtain the magnetic field strength to be $B \simeq 7.5 \mu \text{G}$ with the X-ray flux between 2–10 keV of

<table>
<thead>
<tr>
<th>Target Name</th>
<th>$L_x$</th>
<th>$L_{TeV}$</th>
<th>$L_{TeV}/L_x$</th>
<th>$\Gamma_x$</th>
<th>$\Gamma_{TeV}$</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTB37B (region 2)</td>
<td>0.97</td>
<td>0.59</td>
<td>0.61</td>
<td>1.5</td>
<td>2.3</td>
<td>(1)</td>
</tr>
<tr>
<td>RCW86</td>
<td>3.8</td>
<td>0.55</td>
<td>0.14</td>
<td>3.1</td>
<td>2.5</td>
<td>(2)(3)</td>
</tr>
<tr>
<td>RXJ1713</td>
<td>6.5</td>
<td>0.42</td>
<td>0.06</td>
<td>2.4</td>
<td>2.2</td>
<td>(4)(5)</td>
</tr>
<tr>
<td>VELA Jr.</td>
<td>$\sim 1.5 \times 10^{-2}$</td>
<td>0.033</td>
<td>$\sim 2.2$</td>
<td>2.6</td>
<td>2.1</td>
<td>(6)</td>
</tr>
<tr>
<td>SN1006</td>
<td>2.1</td>
<td>$&lt; 0.15$</td>
<td>$&lt; 0.1$</td>
<td>2.7</td>
<td>$\cdots$</td>
<td>(7)(8)</td>
</tr>
</tbody>
</table>

* Unabsorbed flux in the 2–10 keV band in the unit of $10^{34}$ ergs s$^{-1}$.
† Unabsorbed flux in the 1–10 TeV band in the unit of $10^{34}$ ergs s$^{-1}$.
‡ (1) Aharonian et al. (2006); (2) Bamba et al. (2000); (3) Hoppe et al. (2007); (4) Slane et al. (1999); (5) Aharonian et al. (2004); (6) Aharonian et al. (2005); (7) Bamba et al. (2008); (8) Aharonian et al. (2005b).
§ TeV $\gamma$-ray flux contributed to region 2 was calculated as a quarter of the total flux.
0.78 × 10^{-12} \text{ergs cm}^{-2}\text{s}^{-1} and the TeV \gamma-ray flux between 37–187 TeV of 0.14 × 10^{-12} \text{ergs cm}^{-2}\text{s}^{-1}, respectively. The magnetic field of \(B \simeq 7.5 \mu\text{G}\) is the same as the typical interstellar value of \(\sim 10\mu\text{G}\), that means the origin of TeV \gamma-ray emission is not able to determine by IC or \(\pi_0\) decay.

The roll-off energy obtained from the fitting with the srcut model can be represented with \(B\) and the maximum energy of electrons \(E_{\text{max}}\) as

\[
\nu_{\text{roll}} \simeq 1.6 \times 10^{16} \left( \frac{B}{10 \mu\text{G}} \right) \left( \frac{E_{\text{max}}}{10\text{TeV}} \right)^2 \text{[Hz]} \tag{3}
\]

(Reynolds 1998; Reynolds & Keohane 1999). From this equation, the lower limit of \(E_{\text{max}}\) of region 2 is estimated to be 173 TeV using \(\nu_{\text{roll}} > 14.8 \text{ keV}\) (table 3) and \(B \simeq 7.5 \mu\text{G}\).

7. Conclusion

We have obtained with Suzaku the image and the high quality spectrum of the supernova remnant CTB37B. The X-ray diffuse emission region coincides with that of radio and TeV \gamma-ray. The spectrum consists of thermal and non-thermal components. CTB37B is the second SNR from which thermal and non-thermal X-ray emissions as well as TeV \gamma-ray emission are detected all together, and the fourth SNR that accompanies non-thermal emission both in X-ray and TeV \gamma-ray bands. The thermal emission is described by an NEI model with a temperature and an ionization parameter (\(n_e t\ [\text{cm}^{-3}\text{s}]\)) of 0.9 keV and 3.5 × 10^{10}, respectively. The image size and the observed emission measure provides the number density of the thermal electrons before the shock to be 0.2–0.4 cm^{-3}, which is significantly lower than that of the Galactic plane. The abundances of Mg and Si are subsolar with \(<0.6Z_\odot\). These facts suggest that the supernova explosion associated with CTB37B took place in a low density cavity formed by other SNRs and the shock wave hit a wall of interstellar matter swept by them. From the ionization parameter and the number density of the thermal electron, the age of the plasma is found to be \(\sim 740\ \text{yr}\). This is consistent with the tentative identification of CTB37B with SN393.

In contrast, non-thermal component emitted on the south of CTB37B (region 2) is represented by a power-law model or a srcut model. The photon index of 1.5 is smaller than other non-thermal SNRs. Its spectrum can be connected to the radio one smoothly. The magnetic field strength is obtained to be \(B \simeq 7.5\ \mu\text{G}\) from the flux ratio between TeV \gamma-ray and X-ray on the assumption of IC. This magnetic field strength and the roll-off energy (>15 keV) results in the lower limit of maximum electron energy of \(\simeq 173\ \text{TeV}\). The photon index and the maximum energy suggest that the synchrotron cooling efficiency is lower and/or acceleration efficiency is high.

On the other hand, Chandra observation discovered the point source located near the shell of CTB37B with the photon index of 3.2. Comparing Suzaku and Chandra result, the point source probably has variability.
References

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