The Nature of a Cosmic-Ray Accelerator, CTB 37 B, Observed with Suzaku and Chandra

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Abstract

We report on Suzaku and Chandra observations of the young supernova remnant CTB 37 B, from which TeV γ-rays were detected by the H.E.S.S. Cherenkov telescope. The 80 ks Suzaku observation provided us with a clear image of diffuse emission and high-quality spectra. The spectra revealed that the diffuse emission is comprised of thermal and non-thermal components. The thermal component can be represented by an NEI model with a temperature, a pre-shock electron density and an age of 0.9 ± 0.2 keV, 0.4 ± 0.1 cm⁻³, and 650^{+2500}_{-300} yr, respectively. This suggests that the explosion of CTB 37 B occurred in a low-density space. A non-thermal power-law component was found from the southern region of CTB 37 B. Its photon index of ~1.5 and a high roll-off energy (≥ 15 keV) indicate efficient cosmic-ray acceleration. A comparison of this X-ray spectrum with the TeV γ-ray spectrum leads us to conclude that the TeV γ-ray emission seems to be powered by either multi-zone Inverse Compton scattering or the decay of neutral pions. The point source resolved by Chandra near the shell is probably associated with CTB 37 B, because of the common hydrogen column density with the diffuse thermal emission. Spectral and temporal characteristics suggest that this source is a new anomalous X-ray pulsar.

Key words: acceleration of particles — ISM: individual (CTB 37 B) — 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 ~100 TeV (Koyama et al. 1995). Following this discovery, 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 γ-rays have also been detected from some non-thermal shell-type SNRs. The radiation of TeV γ-rays 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 the fluxes between the TeV γ-rays and the X-rays provides the magnetic field intensity as long as one assumes that the TeV γ-rays are produced through the IC mechanism. Utilizing this characteristic, Matsumoto et al. (2007) found that the TeV γ-rays from HESS J1616–508 are likely to be the result of proton acceleration, because the non-detection of X-rays using the Suzaku XIS provides a much weaker magnetic field than the interstellar average.

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

 CTB 37 B locates at (l, b) = (348°7’, +0°3) with a distance of 10.2 ± 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 the radio band. TeV γ-ray emission is also detected by the H.E.S.S. observation (Aharonian et al. 2007). In spite of evidence of high activities in other wave bands, X-ray observations have been relatively poor. Only ASCA (Tanaka et al. 1994) detected a part of CTB 37 B at the edge of the field of view of the Gas Imaging Spectrometer.
The SNR CTB 37 B with Suzaku

2. Observation and Data Reduction

2.1. Suzaku Observation

CTB 37 B was observed with Suzaku (Mitsuda et al. 2007) during 2006 August 27–29. The nominal pointing position was (RA, Dec) = (17°13′57″, −38°12′15″, J2000.0). 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. The XRT has a point-spread function (PSF) of a Maltese-cross shape with a core radius of ∼15″ accompanied by an outskirts extending a few arcmin. The half-power diameter (HPD) of each telescope is ∼2′. 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 CTB 37 B.

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 × 3 for low and medium data rates and 5 × 5 for high and super-high data rates. In the analysis, we employed 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 efficiency (CTI) correction by ourselves with the xispi software and CTI parameters of 2006–08–23. After screening the data, the effective exposure time was 80 ks in total. Response matrix files (RMF) and ancillary response files (ARF) were made using xisrmgen and xissimarfgen (Ishisaki et al. 2007) version 2007–09–22 under the assumption that the emissions are from a point source.

2.2. Chandra Observation

A Chandra observation was performed on the 2007 February 2 with the Advanced CCD Imaging Spectrometer (ACIS). Chips I0, I1, I2, I3, S2, and S3 were used. The angular resolution is ∼0′.5, which correspond to the CCD pixel size. 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 was 26 ks after screening the data.

3. Image Analysis

3.1. Suzaku Images

Figure 1 shows Suzaku XIS images in 0.3–3.0 keV and 3.0–10.0 keV. They were created by combining those from all the four XIS modules and smoothed with a Gaussian with σ = 12″, which is close to the XRT core size and effective in highlighting the diffuse emission. The source that locates at (l, b) ∼ (348°68, 0°37) appears as the brightest source both in the soft and hard bands. Another source extending to the south of the brightest source, at (l, b) ∼ (348°63, 0°32) seems to be a diffuse source, which manifests itself only in the band above 3 keV. In addition to these sources, a point source is detected at (l, b) ∼ (348°56, 0°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 figure 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 source. Region 2 is the blue ellipse with a major and minor axis of 2′5 and 1′1, respectively, which is 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

Figure 1c shows the Chandra image in the 0.3–10.0 keV band corrected for the telescope vignetting and smoothed with a Gaussian with σ = 6′ to see the point sources clearly. In total, 18 sources were detected above the 5σ confidence level (Aharonian et al. 2008). Panels (d) and (e) are images in 0.3–3.0 keV and 3.0–10.0 keV, respectively, after removing the point sources. They were smoothed with a Gaussian with a σ = 40″ to highlight the diffuse emission. The definition of the colored regions is the same as those drawn in the Suzaku images. The brightest source in region 1 is a point source, which is defined as source A, located at (l, b) = (348°681, 0°371). Although most of the flux from region 1 originates from the point source, it is revealed from figure 1d.
Fig. 1. Images of CTB 37 B in the galactic coordinates. Panels (a) and (b) are Suzaku images in 0.3–3.0 keV and 3.0–10.0 keV, respectively, which are smoothed with a Gaussian with $\sigma = 12''$. Panel (c) is the Chandra image in the 0.3–10.0 keV band being smoothed with a Gaussian with $\sigma = 6''$. Panels (d) and (e) are the Chandra images in 0.3–3.0 keV and 3.0–10.0 keV, respectively. After removing point sources, we smoothed them with a Gaussian with a $\sigma$ of 40''. Solid circles in green, blue, and magenta are the integration region of source photons, which are named as regions 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 x 2.5, and region 3 is a circle with a radius of 1.3. The dashed regions are corresponding background-integration regions.
Table 1. Count rates of sources and diffuse emission of Chandra data.*

| Region | Energy band | Point source count rate $[10^{-2}$ counts $s^{-1}]$ | Diffuse emission count rate $[10^{-2}$ counts $s^{-1}]$ |
|--------|-------------|-----------------------------------------------|-----------------------------------------------|
| region 1 | 0.3–3.0 keV | $2.7 \pm 0.1$ | $3.3 \pm 0.2$ |
| | 3.0–10.0 keV | $2.4 \pm 0.1$ | $0.64 \pm 0.26$ |
| | total | $5.0 \pm 0.1$ | $3.9 \pm 0.4$ |
| region 2 | 0.3–3.0 keV | — | $0.43 \pm 0.15$ |
| | 3.0–10.0 keV | — | $0.93 \pm 0.19$ |
| | total | — | $1.4 \pm 0.2$ |
| region 3 | 0.3–3.0 keV | $2.3 \pm 0.1$ | — |
| | 3.0–10.0 keV | $0.024 \pm 0.021$ | — |
| | total | $2.3 \pm 0.1$ | — |

* All errors are at 1σ confidence level.

that region 1 is accompanied by diffuse emission. These two components are mixed in the Suzaku images. As expected from the Suzaku images in figure 1a and 1b, region 2 is brighter than region 1 in the band above 3 keV. In region 3, there is the second bright source (defined as source B, which is 1RXS J171354.4–381740) located at $(i, b) = (348.5^\circ, 561, 0^\circ332)$, and no diffuse emission is associated in 0.3–3.0 keV band. Table 1 summarizes the background-subtracted source count rates separately for point and diffuse sources in region 1, region 2, and region 3.

3.3. Correlation with Other Energy Band

Figure 2 shows brightness contours of radio at 1.4 GHz in blue and of TeV γ-rays with H.E.S.S. in green, overlaid on the gray scale image of the Suzaku in the 0.3–10.0 keV band. Sources A and B resolved by Chandra are represented by the filled red boxes. The radio image is taken from the NRAO VLA Sky Survey (NVSS) database† (Condon et al. 1998). The X-ray emission well conforms with the shell in radio. Particularly, the diffuse X-ray source detected by Suzaku in region 2 is associated with the southern radio sub-peak. On the other hand, the peak of TeV γ-ray emission and source A seems to be separated from the radio shell. Note, however, that, due to limited spatial resolution of H.E.S.S., the apparent TeV source morphology is consistent with that of the radio shell whose radius is 4·5 (Aharonian et al. 2008).

4. Spectral Analysis

In this section, we present results of a spectral analysis of the three regions described above. We adopt the metal composition of Anders and Grevesse (1989) as the solar abundance. Spectral fits were carried out with XSPEC. We always adopt an ancillary response file (ARF) for a point source, since the sizes of regions 1 and 2 are so small that the resultant spectral parameters including the flux will differ only by ~1% from the case if we take into account the spatial extent. The errors quoted are always at the 90% confidence level.

4.1. Region 1

The Chandra spectrum of source A is shown in figure 3a. In extracting this spectrum, we took a circular integration region with a radius of 3″ centered at the source. We made no background subtraction. Since there is no apparent emission lines, we attempted to fit a power-law model undergoing photoelectric absorption (“phabs” model in XSPEC) to the spectrum. The best-fit model is overlaid in the upper panel of figure 3a as the histogram. The best-fit parameters are summarized in table 2. The photon index, the hydrogen column density, and the intrinsic flux in the 2.0–10.0 keV band are $\gamma = 3.2^{+0.4}_{-0.3}$, $N_H = 4.0(\pm 0.6) \times 10^{22}$ cm$^{-2}$, and $\Phi = 1.8(\pm 0.2) \times 10^{-12}$ erg cm$^{-2}$s$^{-1}$, respectively, which are consistent with those of Aharonian et al. (2008).

Figure 3b is the background-subtracted spectrum of Suzaku region 1. The black and gray crosses represent the data points from the sum of the FI CCDs and those of the BI CCD, respectively. Although there is no sign of Fe Kα emission line in the 6–7 keV band, we have obviously detected Kα emission lines from He-like Mg (1.34 keV), Si (1.86 keV), and S (2.46 keV) as well as a Kβ emission line from He-like Si (2.18 keV). This means that the spectrum includes a thermal-emission component. We

† (http://www.cv.nrao.edu/nvss/).
thus tried to fit the Suzaku spectrum with a model composed of a power law representing source A and a non-equilibrium collisional ionization plasma emission model (“vnei” model in XSPEC; Borkowski et al. 2001; Hamilton et al. 1983; Borkowski et al. 1994; Liedahl et al. 1995) undergoing photoelectric absorption with a common $N_{\text{H}}$. In the fitting, we set abundances of Mg, Si, and S free to vary. The other abundances are fixed as solar abundance. The best-fit parameters are summarized in table 2. The fact that no iron K\textalpha emission line was detected can be attributed that the non-thermal component dominates the spectrum in the energy band above 3 keV. The reduced $\chi^2$ of 1.06 implies that the fit is acceptable at the 90% confidence level. The temperature and the ionization parameter of the “vnei” component are obtained to be $kT = 0.89^{+0.22}_{-0.17}$ keV and $n_\text{e} \Gamma = 3.5^{+11}_{-1} \times 10^{10}$, 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 $3.3^{+0.3}_{-0.4} \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. The photon index is consistent between Suzaku and Chandra, whereas the flux with Suzaku seems to be greater than that with Chandra by a factor of $\sim 1.8$. We remark that, since there is no sign of emission lines in the Chandra spectrum of source A, the thermal component should be extended.

4.2. Region 2

The Suzaku spectra of region 2 together with best-fit model and residual are shown in figure 4. The basic features, such as the Fe emission line and no apparent sign of the He-like Si K\textalpha emission line are similar to those in region 1. In addition to the thermal and non-thermal components, we need to take into account possible contamination from source A, which is brightest in region 1. In fitting the region 2 spectra, we thus first tried a “vnei + power law (1) + power law (2)” model, where the power law (1) accounts for the source A, contamination, and the power law (2) represents a non-thermal component dominating the high-energy band image in region 2 (figure 1). The vnei component, on the other hand, represents the contamination from region 1, and intrinsic thermal

Table 2. Best-fit parameters of the region 1 spectra.

| Parameter | Chandra source A | Suzaku |
|-----------|------------------|--------|
| Power law |                  |        |
| Photon index | $3.2^{+0.4}_{-0.3}$ | $3.0 \pm 0.2$ |
| Intrinsic flux* | $1.8 \pm 0.2$ | $3.3^{+0.3}_{-0.4}$ |
| VNEI |                  |        |
| Temperature [keV] | $\ldots$ | $0.89^{+0.21}_{-0.21}$ |
| Abundance$^\dagger$ Mg | $0.61^{+0.19}_{-0.20}$ | $0.40^{+0.14}_{-0.14}$ |
| Si | $\ldots$ | $1.0 \pm 0.6$ |
| S | $\ldots$ | $3.5^{+13}_{-1}$ |
| $n_\text{e} \Gamma$ | $\ldots$ | $2.1^{+1.6}_{-1.0}$ |
| $EM$ | $\ldots$ | $10^{19}$ |
| $N_{\text{H}}$ | $4.0 \pm 0.6$ | $3.6^{+0.4}_{-0.2}$ |
| $\chi^2$/d.o.f | $14.6/18$ | $176.1/166$ |

* Flux in the 2.0–10.0 keV band in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$.

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

$^\ddagger$ Ionization time-scale in units of $10^5$ s, where $n_\text{e}$ and $r$ are the electron density and age of the plasma.

$\ddagger$ Emission measure $EM = \int n_\text{e} n_\text{H} dV \approx n_\text{e}^2 V$ in units of $10^{58}$ cm$^{-3}$, where $n_\text{e}$ and $V$ are the electron density and the plasma volume. The distance to CTB 37 B is assumed to be 10.2 kpc (Caswell et al. 1975)

$^\dagger$ Absorption column density in units of $10^{22}$ cm$^{-2}$.

Fig. 3. (a) Chandra spectrum integrated from a circular region with a radius of 3″ centered on source A. The best-fit model represented by a power law (histogram) is overlaid. (b) Suzaku spectra of region 1 from the FI-CCDs (black) and the BI-CCD (gray) with a model composed of a “vnei” and a power law model. The best-fit parameters are summarized in table 2.
emission from region 2 if any. Note that the region 2 spectra are statistically poorer than those of region 1. Hence we have fixed the temperature, the abundances of Mg, Si, and S, the ionization parameter of the vnei component and the photon index of power law (1) at the best-fit values obtained in the region 1 fit, which are summarized in table 2. The flux between 2.0–10.0 keV of power law (1) is fixed at 3.3 ± 0.4, where $n_e t$ and $t$ are the electron density and age of the plasma.

### Table 3. Best-fit parameters of the region 2 spectrum.

| Parameters | VNEI + powerlaw + powerlaw | VNEI + powerlaw + srcut |
|------------|----------------------------|--------------------------|
| Temperature [keV] | 0.89 (fix) | 0.89 (fix) |
| Abundance* Mg | 0.61 (fix) | 0.61 (fix) |
| Si | 0.40 (fix) | 0.40 (fix) |
| S | 1.0 (fix) | 1.0 (fix) |
| $n_e t$ | 3.5 (fix) | 3.5 (fix) |
| $EM$ | 0.23 +0.18 | 0.23 +0.14 |
| Photon index | 3.0 (fix) | 3.0 (fix) |
| Intrinsic flux§ | 0.033 (fix) | 0.033 (fix) |
| Photon index | 1.5 ± 0.4 | … |
| Intrinsic flux§ | 0.78 +0.07 | … |
| Alpha | … | 0.5 (fix) |
| Roll-off $E$ [keV] | … | > 14.8 |
| Normalization¶ | … | 1.4 |
| Intrinsic flux¶ | … | 0.78 |
| phabs $N_H$# | 3.5 ±0.5 | 3.5 ±0.5 |
| $\chi^2$/d.o.f | 17.5/48 | 17.5/48 |

* Abundance ratio relative to the solar value (Anders & Grevesse 1989).
† Ionization time-scale in units of $10^{10}$ s cm$^{-3}$, where $n_e t$ and $t$ are the electron density and age of the plasma.
‡ Emission measure $EM = \int n_e n_H dV \approx n_e^2 V$ in units of $10^{58}$ cm$^{-3}$, where $n_e$ and $V$ are the electron density and the plasma volume. The distance to CTB 37 B is assumed to be 10.2 kpc (Caswell et al. 1975)
§ Radio flux at 1 GHz in units of 10$^{-3}$ Jy.
¶ Flux in the 2.0–10.0 keV band in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$.
# Absorption column in units of $10^{22}$ cm$^{-2}$.

We next replaced the power-law (2) component by an “srcut” model, which simulated 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 Kassim et al. (1991) 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. A similar situation has been reported for 30 Dor C (Smith & Wang 2004). 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. As a result, normalization of the srcut model was obtained to be 1.43 mJy at 1 GHz. This is much smaller than the radio flux 26 Jy at 1 GHz. Note, however, that this radio normalization is an integration of the entire radio image of CTB 37 B, part of which is, however, spilt out of regions 1 and 2. Moreover, the radio flux encompassed in region 2 is only $\approx 2\%$ of that in region 1. We therefore estimate the radio flux within region 2 to be $\approx 1\%$ of the total, or $\approx 300$ mJy at 1 GHz. Even after this correction, simple extrapolation of the srcut model well fit to the X-ray spectra to the radio band is much smaller than the observed radio flux. We guess that the flux in the radio band is dominated by thermal emission. The resultant normalization (emission measure) of the vnei component does not change within the error. The reduced $\chi^2$ value is nearly the same as that of the power-law fit. The lower limit of the roll-off energy was 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. Based on these results, it is possible to interpret that the spectrum of
the non-thermal component extends from X-rays to radio with an energy index of 0.5 in the radio band.

4.3. Region 3

Figure 5 shows the background-subtracted spectra of region 3. As indicated by the images in figure 1a, X-ray flux is detected only below $\sim 3$ keV. Since the absorption is apparently weak and there is a 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 a model composed of a thin thermal collisional equilibrium plasma emission model (“mekal” model in XSPEC: Mewe et al. 1985, 1986; Liedahl et al. 1995; Kaastra et al. 1996) multiplied by photoelectric absorption, and fitted this model to the spectra in the 0.5–2.0 keV band. The result is shown in figure 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 can probably be attributed to the calibration uncertainty.

5. Timing Analysis

In order to understand the nature of the point sources, we carried out a timing analysis.

5.1. Source A

We searched the Chandra data for a pulsation from source A. Unfortunately, source A locates close to the chip boundaries of the ACIS-I, and is affected by the instrumental dithering effects. In fact, the source drops into the boundary every 1000 s, during which the source count diminishes significantly. Removing these time intervals with a Good Time Interval filtering, we made a light curve and searched for pulsation. The power spectrum on the basis of a 3.2 s binning light curve in the 0.3–10 keV band is shown in figure 6. We did not detect any pulsation in the period range between 6.6–3000 s.

5.2. Source B

We created a light curve of source B in the 0.5–2.0 keV band with Suzaku, which is shown in figure 7. The time bin size is 512 s. 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.

Fig. 5. XIS spectra of region 3 with the MEKAL model.

Table 4. Best-fit parameters of the region 3 spectrum.

| MEKAL                  |                         |                        |
|------------------------|-------------------------|------------------------|
| Temperature [keV]       | 0.46$^{+0.03}_{-0.05}$  | 0.20$^{+0.12}_{-0.07}$ |
| Abundance              | 2.5$^{+1.4}_{-0.6}$     | $< 0.046$              |
| Normalization$^\dagger$| $< 10^{22}$ cm$^{-2}$   | $< 10^{22}$ cm$^{-2}$  |
| $\chi^2$/d.o.f         | 52.9/27                 | 52.9/27                |

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

Power spectrum of source A in the 0.3–10.0 keV band with the time bin size of 3.2 s.

Light curve of region 3 in the 0.5–2.0 keV band. The time bin size is 512 s.
6. Discussion

6.1. Thermal Component

We calculated the electron number density and the age of the diffuse thermal plasma of regions 1 and 2 on the basis of the best-fit parameters summarized in tables 2 and 3. We assumed that the plasma in region 1 distributes uniformly within a sphere with a radius of 1.4, which is the Half-Width-at-Half-Maximum (HWHM) radius obtained from the Chandra image (Aharonian et al. 2008). Assuming the distance to CTB 37 B to be 10.2 kpc (Caswell et al. 1975), we obtained the real radius of region 1 to be \( r_{\text{reg1}} = 1.3 \times 10^{19} \text{cm} \). Accordingly, the volume of the region 1 plasma is \( V_{\text{reg1}} = (4/3)\pi r_{\text{reg1}}^3 = 9.2 \times 10^{57} \text{cm}^3 \). In the same way, from HWHM of an estimated image size of 1.9 \( \times \) 0.9, the real length of the semi-major and semi-minor axes result in \( r_{\text{reg2}} = 1.7 \times 10^{20} \text{cm} \) and \( r_{\text{reg2}} = 8.2 \times 10^{18} \text{cm} \), respectively. Assuming that the line-of-sight extent of region 2 is \( r_{\text{reg2}} = 2.0 \times 10^{19} \text{cm} \), the volume of region 2 is calculated to be \( V_{\text{reg2}} = (4/3)\pi r_{\text{reg2}}^3 r_{\text{reg2}} = 4.8 \times 10^{57} \text{cm}^3 \) (the resultant electron density becomes smaller by a factor of \( \sqrt{2} \) if we substitute \( r_{\text{reg2}} \) for \( r_{\text{reg2}} \)). With the aid of the emission measures obtained from the spectral fitting, \( EM = \int n_e n_H dV = 2.1^{+1.6}_{-1.0} \times 10^{58} \text{cm}^{-3} \) (region 1) and \( 2.6 \times 10^{57} \text{cm}^{-3} \) (region 2 upper limit, see subsection 4.2), the electron number density of regions 1 and 2 are

\[
n_{e,\text{reg1}} = 1.7 \left( 1.2 - 2.2 \right) \text{[cm}^{-3}] \tag{1}
\]

and

\[
n_{e,\text{reg2}} \leq 0.82 \text{[cm}^{-3}] \tag{2}
\]

where we adopt the relation \( n_e \approx 1.24 n_H \) for fully ionized plasma. The parameter region in parentheses is that allowed at the 90% confidence level. Assuming the strong shock, we obtained the pre-shock densities to be \( 0.43 \text{ cm}^{-3} \) and \( 0.21 \text{ cm}^{-3} \), respectively, which are significantly lower than the average density of the interstellar matter in the galactic plane. This means CTB 37 B exploded in a low-density space. The density of region 1 together with the ionization parameter obtained from the fit of the region 1 spectra \( n_{e,\text{reg1}} t = 3.5^{+13}_{-11} \times 10^{10} \text{[cm}^{-3}\text{s}] \), enabled us to estimate the age of the plasma observationally for the first time as

\[
r_{\text{reg1}} = 6.5(3.7 - 31) \times 10^2 \text{[yr]} \tag{3}
\]

CTB 37 B is one of the best candidates of SN 393 in the 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 regions 1 and 2 are \( N_{e,\text{reg1}} = 1.6(1.1 - 2.0) \times 10^{58} \) and \( N_{e,\text{reg2}} \leq 3.9 \times 10^{57} \). As a result, the total mass included in the two regions are 15(11 – 20) \( M_\odot \) and \( \leq 3.7 M_\odot \), respectively, and the thermal energy \( E = \frac{3}{2} (N_e + N_H + N_{H_e}) kT \) are

\[
E_{\text{reg1}} = 6.4(4.1 - 8.6) \times 10^{49} \text{[erg]}, \tag{4}
\]

\[
E_{\text{reg2}} \leq 1.6 \times 10^{49} \text{[erg]}, \tag{5}
\]

under the assumption of energy equipartition between electrons and ions. The total thermal energy could be larger if other portions of the remnant are included, and if the proton temperature is significantly larger than the electron temperature, as is expected for supernova remnants with large shock velocities (Ghavamian et al. 2007).

6.2. The Nature of the Point Sources

6.2.1. Source A

The best-fit spectral parameters of Chandra source A and those of Suzaku region 1 (source A and the diffuse thermal emission) are summarized in table 2. The measured hydrogen column densities \( (N_H \approx 4 \times 10^{22} \text{cm}^{-2}) \) are the same between Chandra and Suzaku. However, since the Suzaku spectra below \( \approx 1 \text{ keV} \) is dominated by the diffuse thermal component (figure 3), \( N_H \) obtained with Suzaku is determined mainly by the diffuse emission. This implies that source A is probably associated physically with the diffuse thermal emission in region 1, and is most likely a neutron star (or a black hole) born with the supernova explosion leading to CTB 37 B. In fact, the large photon index of 3.2 and luminosity of \( 2.2 \times 10^{38} \text{ erg s}^{-1} \) are both consistent with those of anomalous X-ray pulsar (AXP: Fahlman & Gregory 1981; Kuiper et al. 2006). Young age of \( \sim 700 \text{ yr} \) (subsection 6.1) also supports this interpretation (e.g. the AXP 1E1841 – 045 is associated with Kes 73 whose age is estimated to be 500 – 1000 yr: Tian & Leahy 2008). Since the spin period of AXP is in the range 6–12 s, it is natural that we have found no evidence of pulsation from the Chandra data, because the frame time of the ACIS-I is 3.2 s. In addition, the flux of the power law measured by Suzaku is apparently greater that that with Chandra by a factor of 1.8 (subsection 4.1, table 2). Note that the point spread function of the Suzaku XRTs is not so sharp. Hence, one may doubt that part of the power-law flux detected by Suzaku can be attributed to a putative diffuse non-thermal emission. However, \( \sim 80\% \) of the Chandra region 1 photons above 3 keV, where the power-law component is dominant in the Suzaku spectra (see figure 3), originates from source A (table 1). Since the diffuse emission occupies only a small fraction in region 1, the flux difference between Chandra and Suzaku cannot be explained unless source A has really varied. This kind of long-term variation is also detected from some other AXPs (Gavriil & Kaspi 2002; Kaspi et al. 2003). We therefore conclude based on the Chandra and Suzaku observations that source A is probably a new AXP. We need a fast timing observation with an imaging detector with a time resolution of less than 1 s to confirm our conclusion.

6.2.2. Source B

From the spectrum fitting, the hydrogen column density obtained from the fit to the Suzaku region 3 spectra \( N_H < 4 \times 10^{20} \text{cm}^{-2} \) (table 4) is much smaller than that obtained from regions 1 and 2. This result indicates that source B is a foreground source. The best-fit plasma temperature of \( kT \approx 0.5 \text{ keV} \) is reminiscent of an active star. The existence of flickering (subsection 5.2) supports this suggestion.

6.3. Non-Thermal Component

X-ray emission from CTB 37 B is composed of the diffuse thermal component (region 1) and the non-thermal component (region 2) as well as a point source (source A), as demonstrated in section 3 and section 4. Hence, CTB 37 B now is the
third SNR after RCW 86 and Cas A that possesses the thermal and non-thermal X-ray emissions and TeV γ-ray emission all together. In addition, CTB 37 B is now the fifth SNR, following RCW 86, Cas A, RX J1713.7–3946, and Vela Jr., from which non-thermal radiation is detected both in X-ray and TeV γ-ray bands. The fluxes of the non-thermal emission of these five non-thermal SNRs are compared in table 5.

The non-thermal diffuse component detected from region 2 has a remarkably flat X-ray spectrum with a photon index of 1.5. Since this photon index is equal to the typical radio photon index (energy index $\alpha = 0.5$), the non-thermal emission spectrum can be considered as extending from the radio band smoothly to the X-ray band, thereby the roll-off energy results in as high as $\gtrsim 15$ keV (table 3). This roll-off energy is higher than any other SNR that is accompanied by the non-thermal X-ray and TeV γ-ray emission, such as $\lesssim 9$ keV for RX J1713.7–3946 (Takahashi et al. 2008), $\sim 0.23$ keV for SN 1006 (Bamba et al. 2008), $\sim 0.87$ keV for RCW 86 (Bamba et al. 2005). This indicates high electron acceleration efficiency in region 2. In addition, the density around region 2 is considered to be lower than in region 1, given that only the upper limit of the thermal emission is obtained (subsection 6.1). The lower density may indicate higher shock velocity due to the smaller deceleration, which is consistent with the fact that the roll-off frequency is proportional to the square of the shock velocity (Aharonian & Atoyan 1999).

It should be a matter of debate whether the TeV γ-ray emission and the non-thermal X-ray emission from region 2 are produced by the same population of electrons, since the images of these two bands shown in figure 2 are far from similar at first sight. The TeV γ-ray image is compatible with a shell with a radius of $\sim 4′$–$6′$ due to limited spatial resolution of H.E.S.S. (Aharonian et al. 2008), which is compatible with the size of the radio shell. We thus assume that the TeV γ-ray emission is powered through 1-zone Inverse Compton scattering (IC) of the cosmic microwave background due to the accelerated electrons.

The maximum electron energy ($E_{\text{max}}$) can be evaluated by the shape of TeV γ-ray spectrum. Using the H.E.S.S. spectrum whose photon index is 2.3 (Aharonian et al. 2006) shown in figure 8 in blue, we determined $E_{\text{max}}$ of 10 TeV. The red line in figure 8, on the other hand, is the X-ray power-law spectrum of region 2 with a photon index of 1.5. A series of the dashed plots are the model spectra calculated under the assumptions of $E_{\text{max}}$ of 10 TeV, an index of the electron energy distribution of 2, and various magnetic field (0.1, 1.0, and 10.0 $\mu$G). It is clear from this figure that 1-zone IC model is unable to explain the synchrotron X-ray spectrum with any magnetic field strength. This suggests that TeV γ-ray emission is due to multi-zone IC scattering, or the decay of neutral pions generated by the high-energy proton impacts.

7. Conclusion

We obtained with Suzaku images and high-quality spectra of the supernova remnant CTB 37 B. The X-ray diffuse emission region coincides with that of radio and TeV γ-rays. The X-ray emission consists of thermal and non-thermal diffuse components as well as a point source resolved by Chandra. CTB 37 B is the third SNR from which thermal and non-thermal X-ray emissions as well as TeV γ-ray emission are detected all together, and the fifth SNR that is accompanied by non-thermal

Table 5. Comparison of non-thermal component with other SNRs.

| Target name     | $L_x$ $^a$ | $L_{\text{TeV}}$ $^b$ | $L_{\text{TeV}}/L_x$ | $\Gamma_x$ | $\Gamma_{\text{TeV}}$ | References $^c$ |
|-----------------|------------|-----------------------|-----------------------|-----------|-----------------------|----------------|
| CTB 37 B (region 2) | 0.97       | 0.59                  | 0.61                  | 1.5       | 2.3                   | (1)            |
| RCW 86          | 3.8        | 0.55                  | 0.14                  | 3.1       | 2.5                   | (2)(3)         |
| Cas A           | 110        | 0.21                  | 0.0019                | 3.1       | 2.4                   | (4)(5)         |
| RX J1713        | 6.5        | 0.42                  | 0.06                  | 2.4       | 2.2                   | (6)(7)         |
| VELA Jr.        | ~1.5 $\times$ 10$^{-2}$ | 0.033               | ~2.2                  | 2.6       | 2.1                   | (8)            |
| SN 1006         | 2.1        | < 0.15                | < 0.1                 | 2.7       | …                     | (9)(10)        |

$^a$ Unabsorbed flux in the 2–10 keV band in units of 10$^{34}$ erg s$^{-1}$.
$^b$ Unabsorbed flux in the 1–10 TeV band in units of 10$^{34}$ erg s$^{-1}$.
$^c$ (1) Aharonian et al. (2006); (2) Bamba et al. (2000); (3) Hopper et al. (2007); (4) Helder et al. (2008); (5) Albert et al. (2007); (6) Slane et al. (1999); (7) Aharonian et al. (2004); (8) Aharonian et al. (2005a); (9) Bamba et al. (2008); (10) Aharonian et al. (2005b)
emission both in X-ray and TeV γ-ray bands.

The diffuse thermal emission can be best described by a non-equilibrium collisional ionization plasma model (NEI model) with a temperature, an ionization parameter \([n_t \times (cm^{-3} s)]\), and abundances of \(0.9 \pm 0.2 \text{ keV, 3.5 }^{+13}_{-11} \times 10^{10}\), and \(\sim 0.5 Z_{\odot} (\text{Mg, Si})\), respectively. The image size and the observed emission provide the number density of the thermal electrons before the shock to be \(0.2-0.4 \text{ cm}^{-3}\), which is significantly lower than that of the galactic plane. This suggests that the supernova explosion associated with CTB 37 B took place at a low density space. From the ionization parameter and the number density of the thermal electron, the age of the plasma is found to be \(\sim 650^{+2500}_{-1000}\) yr. This is consistent with the tentative identification of CTB 37 B with SN 393 within the error.

In contrast, the diffuse component occupying southern part of CTB 37 B (region 2) is non-thermal, and represented by a power-law model or a srcut model. The photon index of 1.5 is significantly smaller than any other non-thermal SNR, but is consistent with that of a typical non-thermal SNR in the radio band. The srcut model fit with its normalization set free to vary therefore results in a high roll-off energy of \(> 15 \text{ keV}\).

Under the assumption that TeV γ-rays were emitted by 1-zone IC scattering, there are no solutions for the magnetic field strength that can reproduce the observed synchrotron spectrum in X-rays. This suggests that TeV γ-rays are produced by multi-zone IC scattering, or by the decay of neutral pions generated by the high energy proton impacts.

Owing to the high spatial resolution of Chandra, a point source is resolved from the brightest part of the Suzaku image of CTB 37 B (region 1). Its association to the diffuse thermal emission indicated by \(N_{\text{H}1}\), the photon index of \(\sim 3\), the X-ray luminosity of order \(10^{34} \text{ erg s}^{-1}\), and the long term flux variation evident from the Chandra and Suzaku observations all indicate that the point source is a new anomalous X-ray pulsar. A high-speed photometric observation is encouraged.

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