Detection of X-Ray Emission from the Unidentified TeV Gamma-Ray Source TeV J2032+4130

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Abstract

We observed the first unidentified TeV $\gamma$-ray source TeV J2032+4130 with Suzaku. Owing to Suzaku’s high sensitivity for the detection of diffuse X-ray emission, we found two small structures in the TeV emitting region. One of them is coincident with a $\gamma$-ray pulsar, PSR J2032+4127, which was discovered by the Fermi Gamma-ray Space Telescope. By subtracting the contribution of point sources estimated by Chandra data, we obtained the diffuse X-ray spectrum. The X-ray spectrum can be reproduced by a power-law model with a photon index of $\sim$2, and an X-ray flux of $2 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$. The ratio of the $\gamma$-ray flux to the X-ray flux is about 10. If the origin of the TeV $\gamma$-rays is inverse Compton scattering of the microwave background by high-energy electrons, the ratio corresponds to a magnetic field strength of $\sim$1 $\mu$G. However, the smaller size of the X-ray emission than that of the TeV emission suggests that the energy loss of the electrons can explain the large ratio of the $\gamma$-ray flux with a reasonable magnetic field strength of a few microgauss.

Key words: acceleration of particles — pulsars: individual (PSR J2032+4127) — X-rays: individual (TeV J2032+4130) — X-rays: ISM

1. Introduction

The stereoscopic technique of atmospheric Cerenkov telescopes improved the angular resolution for detecting TeV $\gamma$-rays, and thus increased the number of TeV $\gamma$-ray sources. Some of the new TeV objects have no counterparts at other wavelengths, and are called unidentified TeV $\gamma$-ray objects. These objects provide key information in investigations of the origin of high-energy cosmic rays. Multi-wavelength observations of these objects are very important for elucidating the emission mechanism and successful identification of them.

TeV J2032+4130 was the first unidentified TeV $\gamma$-ray source discovered by HEGRA (Aharonian et al. 2002). The TeV emission exhibits a significant extension with a radius of 6.2 and a center of gravity of $(RA, Dec) = (20^h31^m57^s0, 41^\circ29'56''8)$ (Aharonian et al. 2005a). The position is coincident with an OB association, Cygnus OB2, and located north of a microquasar, Cyg X-3. These two sources had been suggested to be possible origins of TeV $\gamma$-rays, but no firm evidence to determine the counterpart has been found. TeV $\gamma$-ray emission of this region has also been reported by other telescopes: Whipple, MAGIC, and Milagro (Konopelko et al. 2007; Albert et al. 2008; Abdo et al. 2007).

In the X-ray band, Chandra and XMM-Newton observed the TeV J2032+4130 region. The first observation by Chandra detected 27 point sources within the observed field ($\sim$17’) with an exposure time of 5 ks (Mukherjee et al. 2003, MHG2003 hereafter). Butt et al. (2003) also resolved 19 point sources above the threshold of 2.5 $\sigma$ by adapting the wavdetect tool to the same data. Then, a follow-up deeper 50 ks observation remarkably increased the number of detected sources: 240 sources in almost the same field (Butt et al. 2006, Butt2006 hereafter).

XMM-Newton also detected many point sources in a wider FOV ($\sim 30\arcmin$). By subtracting the contribution of detected point sources, Horns et al. (2007) indicated a hint of diffuse emission extending about the size of TeV emission region. However, this result may still include contributions of faint point sources that were resolved by Chandra, due to the moderate angular resolution of XMM-Newton.

The detection of a diffuse X-ray emission for the 50 ks Chandra data has also been reported by Mukherjee, Gotthelf, and Halpern (2007) with the same analysis technique. However, the spectral model can not be constrained because of the low photon statistics observation by Chandra.

Recently, the Large Area Telescope on the Fermi Gamma-ray Space Telescope detected $\gamma$-rays from this region, with energy from 20 MeV to 300 GeV (1FGL J2032.2+4127: Abdo et al. 2010a). In addition, this $\gamma$-ray source showed pulsation with a pulse period of 143 ms (PSR J2032+4127: Abdo et al. 2009, 2010b). Subsequent observations of a radio band also detected a pulsation with the consistent position and the pulse frequency of the $\gamma$-ray pulsar. The position of...
the pulsar is coincident with the optical point source of the number 213 in Massey and Thompson (1991) (MT 91 213: Camilo et al. 2009).

These results imply that the origin of TeV $\gamma$-rays also relates to this $\gamma$-ray pulsar. Active pulsars are losing a significant part of energy via relativistic particles, and forms pulsar wind nebulae (PWNe). PWNe emit synchrotron radiation from the radio to X-ray bands. In addition, some PWNe are found to be TeV emitters (Gaensler & Slane 2006; Kargaltsev & Pavlov 2010). Thus, PSR J2032+4127 is a possible candidate for the counterpart of TeV J2032+4120.

The distance to PSR J2032+4127 is estimated to be 3.6 kpc by measuring the dispersion measure in the radio band (Camilo et al. 2009). However, the distance to the Cygnus OB2 is estimated to be 1.7 kpc by a spectroscopic observation of OB stars (Hanson 2003). We adopt the former value as the distance to the X-ray emission.

In this paper, we report on X-ray observations of TeV J2032+4130 with Suzaku, which has a higher sensitivity for detecting diffuse X-ray emission with the large effective area and the low stable background. We analyzed the diffuse X-ray spectrum of the PWN in detail.

Though Suzaku has an advantage for detecting diffuse X-ray sensitivity, the angular resolution is not sufficient to resolve point sources. To properly estimate the contribution of point sources, we also reanalyzed the Chandra data. There are many point sources in and near the Cygnus OB2 region, which are one of the candidates for the origin of TeV emission (e.g., Butt2006). We resolved point sources within strict parameters, and subtracted the point-source flux from the diffuse emission. Thus, we investigated the diffuse emission by the combination of Suzaku and Chandra.

2. Observations

2.1. Suzaku

We observed the TeV J2032+4130 region with Suzaku (Mitsuda et al. 2007) on 2007 December 17 and 18. Suzaku has a moderate angular resolution and a large effective area. This characteristic is suitable for detecting weak diffuse emission. The observations were made using three CCD cameras (X-ray Imaging Spectrometer, XIS: Koyama et al. 2007) on the focal planes of the X-Ray Telescopes (XRT: Serlemitsos et al. 2007). One of the cameras (XIS 1) has a back-illuminated (BI) CCD, and the others (XIS 0, 3) contain front-illuminated (FI) CCDs. Each of the XIS sensors was operated in the normal clocking mode with the $5 \times 5$ or $3 \times 3$ editing mode.

We used clean events processed with the pipeline version of 2.1.6.16. Data taken during the passage through the South Atlantic Anomaly, at elevation angles of less than 5° from the night Earth rim, or 20° from the day Earth rim were excluded. After this filtering, the net observing time was about 40 ks.

2.2. Chandra

Chandra observed the TeV J2032+4130 region twice: an earlier short observation (2002 August 11, obsid = 4358) and a deep follow-up observation (2004 July 19, obsid = 4501). The exposure times were 5 ks and $\sim 49$ ks, respectively. Chandra has a superior angular resolving capability. We analyzed Chandra data in order to estimate the contribution of point sources, using the Chandra Interactive Analysis of Observations (CIAO) software version 4.0.2 with CALDB version 3.4.3. The detailed results about the Chandra observations have already been reported in Butt2006.

3. Results

3.1. Images

We first constructed a total energy band image of the TeV J2032+4130 region with Suzaku data. Figure 1 shows an XIS image of the 0.5–10.0 keV band. All three CCD data were combined. A dashed circle indicates the TeV diffuse emission region (Aharonian et al. 2005a).

There are two diffuse structures in the circle (structures 1 and 2 in figure 1). The extent of X-ray emission is significantly larger than the point spread function. Assuming a Gaussian profile, their sizes are $\sim 1.1$ for both structures; however, they are much smaller than the TeV emission.

These X-ray emitting structures are located at the south eastern part of the TeV $\gamma$-ray region, and are included in the OB star association Cygnus OB2 (dotted circle in figure 1). There must be many point sources in the field. We estimated the contribution of the point sources by using the Chandra deep exposure data, which has superior angular resolution, and can resolve weak point sources.

We extracted point sources by the CIAO “wavdetect” software of a wavelet method (Freeman et al. 2002). The threshold significances of wavdetect were set at $10^{-6}$ for the source list and at 0.001 for the background estimation. The wavelet scales were $\sqrt{2}$, 2, 2$\sqrt{2}$, 4, 4$\sqrt{2}$, 8, 8$\sqrt{2}$, and 16 pixels. We then resolved 254 point sources from the whole region of ACIS-I CCDs. The structure 1 region includes 8 sources, while the structure 2 region includes 2 sources; 158 sources are located in the TeV $\gamma$-ray region (dashed circle in figure 1), excluding structures 1 and 2.

Figure 2 shows a Chandra image around structure 1. Point...
sources are indicated by solid ellipses with the source numbers in Butt2006. #129 is coincident with the γ-ray pulsar discovered by Fermi (Camilo et al. 2009).

3.2 Spectra

First, we constructed a spectrum of point sources by Chandra observations in order to estimate the contribution of point sources in the Suzaku image. We collected all of the events from the point sources in structures 1, 2, and the remainder of the TeV γ-ray emitting region. X-ray photons were extracted from an ellipse with the axes of 3σ of the 2-D Gaussian calculated by wavdetect for each source. To reproduce spectra, we fit the spectrum using a phenomenological model of a power-law with interstellar absorption. The best-fit parameters are given in “point sources” rows in table 1.

We then constructed a spectrum of diffuse emission using Suzaku data. The extracted spectrum of structure 1 is shown in figure 3a. The spectra and responses of three CCDs were combined. We included the contribution of the point sources by adding its best-fit model into the model spectrum, which is indicated by the blue dotted line in figure 3a. Thus, we obtained best-fit parameters of diffuse X-ray emission for structure 1 (table 1). The spectrum can be reproduced by an absorbed power-law with a photon index (Γ) of 2.1, and an absorption column (N_H) of 0.6 × 10^{22} cm^{-2}. The X-ray flux is about 2.0 × 10^{-13} erg s^{-1} cm^{-2} (2.0–10.0 keV).

We also derived best-fit parameters of X-ray spectra extracted from structure 2 and from the remainder in the same manner (table 1). Best-fit models of diffuse and point sources are plotted in figures 3b and 3c. The absorption-corrected luminosities (2–10 keV) of the diffuse components are 3.1 × 10^{32} erg s^{-1}, 3.0 × 10^{32} erg s^{-1}, and 14 × 10^{32} erg s^{-1}, for structures 1, 2, and the remaining region, respectively.

In structures 1 and 2, the spectra of point sources are softer than the diffuse component. This indicates that the point-source rejection method works properly. It also implies that the origin of diffuse X-ray emission is not a concentration of faint point sources. Most of the point sources in structures 1 and 2 are stars, which generally exhibit softer X-ray emission. The typical temperature of the Cygnus OB2 stars is 1.35 keV (Albacete Colombo et al. 2007). Indeed, the spectra of the point sources in structures 1 and 2 can be represented by a thin thermal plasma model with a temperature of ∼1 keV.
3.3. Time Variation of Point Sources

We estimated the contribution of point sources using the Chandra data. However, there is an uncertainty in the estimated flux because of a possible long-term variability of the sources. Indeed, Mukherjee, Gotthelf, and Halpern (2007) reported the detection of transient X-ray sources in the TeV emission region. We evaluated the uncertainty from two Chandra observations of TeV J2032+4130 region: an initial 5 ks observation in 2002 (MHG2003) and a deep follow-up exposure of 50 ks in 2004 (Butt2006). We compared the X-ray count rate of point sources between these two observations.

The earlier observation has poor photon statistics, and detected only 2 sources inside of structure 1. These sources are #17 and #18 in MHG2003. A follow-up observation detected 7 point sources within the same field, as shown in figure 2. We made the identification between two observations by the coordinates of these sources; #70 in Butt2006 is coincident with MHG2003 #17. These sources are identical. However, there are two sources at the position of MHG2003 #18, #15 and #47 in Butt2006. These sources were too close to be resolved in the earlier observation. We consider the count rate of #18 in MHG2003 to be the total of these two sources. Structure 2 only includes the identification of #14 in MHG2003. This source is coincident with #150 in Butt2006. We summarize the count rates of these sources in table 2.

The count rate of MHG2003 #17 is 3.0 x 10^{-3} counts s^{-1} in 2002, and 1.5 x 10^{-3} counts s^{-1} in 2004. The time variation is ~2. For MHG2003 #18, the count rate is 7.0 x 10^{-3} counts s^{-1} in 2002, which is similar to 7.2 x 10^{-3} counts s^{-1}, the combined count rate of #15 and #47 in Butt2006.

The count rate of MHG2003 #14 in structure 2 is ~4.4 x 10^{-3} counts s^{-1} in 2002 and 0.62 x 10^{-3} counts s^{-1} in 2004. The point source indicates time variability as large as a factor of 7.

As shown in table 1, the contribution of the point sources is about 16.5% and 1.3% for structures 1 and 2, respectively. Even in the largest case of the time variety obtained above (factors 2 and 7), the contribution is about 33% and 9%, respectively. Although these uncertainties of the point-source fluxes have an influence on the spectrum analysis of diffuse emission, the diffuse emission cannot be explained by the point sources.

### Table 1. Best-fit parameters of X-ray spectra.*

| Structure | Point Sources | $N_{H}$ ($10^{22}$ cm$^{-2}$) | $\Gamma$ | $F_X$ ($10^{-13}$ erg s$^{-1}$ cm$^{-2}$) | $L_X$ ($10^{33}$ erg s$^{-1}$) | $\chi^2$ (d.o.f) |
|-----------|--------------|-------------------------------|---------|------------------------------------------|----------------------------|------------------|
| Structure 1 | diffuse | 0.6 $^{+0.2}_{-0.3}$ | $3.1^{+0.5}_{-0.4}$ | 0.32 $^{+0.03}_{-0.02}$ | 23.0 (14) |
| Structure 1 | point sources | 0.4 $^{+0.8}_{-0.4}$ | 0.025 $^{+0.006}_{-0.02}$ | 0.70 (3) |
| Structure 2 | diffuse | 0.6 $^{+0.3}_{-0.2}$ | 0.19 $^{+0.5}_{-0.2}$ | 3.0 $^{+0.3}_{-0.2}$ | 11.5 (6) |
| The remain | diffuse | 0.7 $^{+0.2}_{-0.3}$ | 0.22 $^{+0.4}_{-0.3}$ | 14 $^{+0.8}_{-0.7}$ | 28.3 (24) |

* The uncertainties are 90% confidence level.
† X-ray flux in the 2–10 keV band.
‡ Absorption corrected X-ray luminosity in the 2–10 keV band. The distance is assumed to be 3.6 kpc.

### Table 2. Comparison of the X-ray count rate of point sources derived from Chandra data.*

| Identification | Count rate ($\times 10^{-3}$ counts s$^{-1}$) | MHG2003 | Butt2006 |
|----------------|---------------------------------------------|---------|----------|
| Structure 1    |                                             | 2002    | 2004     |
| #17            |                                             | 3.0     | 1.5      |
| #70            |                                             |         |          |
| Structure 2    |                                             |         |          |
| #14            |                                             | 4.4     | 0.62     |
| #15            |                                             | 7.0     | 4.8      |
| #47            |                                             | 2.4     |          |
| #150           |                                             |         |          |

* The time variations of MHG2003 #17 and #14 are ~2 and ~7, respectively. MHG2003 #18 is considered to be a combination of two point sources #15 and #47 in Butt2006.

4. Discussion

We obtained X-ray spectrum of diffuse emission around the $\gamma$-ray pulsar PSR J2032+4127 (structure 1). The photon index is determined to be ~2. This value is coincident with the typical index of the X-ray spectrum from PWN: $\Gamma \simeq 1–2$ (Kargaltsev & Pavlov 2008). In this section, we consider that diffuse X-ray emission is radiated by the pulsar wind nebula, and discuss the radiation mechanism.

4.1. Energy Injection

First, we discuss the energy injection rate. The spin-down power of the $\gamma$-ray pulsar, PSR J2032+4127, is calculated to be about $2.63 \times 10^{35}$ erg s$^{-1}$ (Abdo et al. 2010b). Meanwhile, the isotropic luminosity of the GeV $\gamma$-ray pulsar is $1.4 \times 10^{35}(d/3.6$ kpc)$^2$ erg s$^{-1}$ (Camilo et al. 2009), where $d$ is the distance to the pulsar. At most, about half of the energy is emitted as GeV $\gamma$-rays with an assumption of isotropic radiation. The ratio can be smaller in the case of collimated radiation. The intensity of off-pulse emission is almost the same as the background level, which is estimated from the surrounding annulus region of the pulsar (figure A-42 in Abdo et al. 2010b). Indeed, a detailed analysis of off-pulse spectrum cannot constrain the flux level (Ackermann et al. 2011). A large portion of GeV $\gamma$-rays originates from the pulsar’s magnetosphere, and the luminosity of PWN is negligible in this energy band. Consequently, we cannot obtain a meaningful...
4.2. Emission Mechanism

In figure 4, we plot the fluxes of X-rays and TeV γ-rays. The X-ray flux is indicated by a best-fit model of the diffuse component spectrum of structure 1. The ratio of the flux between the TeV and the X-ray bands, \( F_{\text{TeV}} / F_X \), is ~10:1. Although TeV γ-ray emission dominates the X-ray flux in some PWNe (Funk et al. 2007; Kargaltsev et al. 2009; Mukherjee et al. 2009), it is difficult to explain such a large ratio with a simple energy distribution of high-energy electrons.

If the origin of TeV γ-ray emission is inverse Compton scattering of the cosmic microwave background (CMB) by TeV electrons, the same high-energy electrons also emit X-rays by synchrotron radiation. In this case, the ratio of the TeV flux to the X-ray flux depends only on the magnetic field strength. The synchrotron emission model of TeV electrons is shown by solid lines in figure 4 for some assumed magnetic fields of 1, 3, and 10 µG. Our data corresponds to a magnetic field of about 1 µG. However, this value is much lower than that expected in this region. The total magnetic field strength in the galaxy disk is larger than 3 µG in the whole area (Beck 2001). In addition, the active star-forming region indicates a stronger magnetic field.

If the photon energy density of the local radiation field is much higher than CMB, Compton-scattered TeV γ-rays exhibit a larger intensity, and might explain our data. The number of OB stars is ~1000 in the Cygnus OB2 region. Although we could not rule out the possibility of strong radiation background, we only consider CMB in this study.

One possibility for resolving the discrepancy is a hadronic origin of TeV γ-ray emission (e.g., Bednarek & Bartosik 2003). In such a case, X-ray emission can be much lower than in the leptonic case, and a typical strength of magnetic field of PWNe, 3 µG, could be acceptable.

Another possibility is the existence of a high-energy cut-off of electrons. The energy of electrons, which is responsible for TeV emission, is lower than X-ray emitting electrons by about one order of magnitude. If the energy distribution of TeV electrons exhibits a strong cut-off above the TeV region, the flux of X-ray emission is decreased (dashed line in figure 4). Mattana et al. (2009) investigated the evolution of the PWNe by comparing 14 samples, and concluded that the ratio of the TeV and X-ray luminosities has a positive correlation with the characteristic age of the pulsar. The X-ray luminosity decreases with the pulsar age because of radiative cooling in the earlier stage (by a factor \( \sim 10^5 \) in 10^5 yr), while the γ-ray luminosity is constant. Thus, the ratio becomes larger. PSR J2032+1217 is an old pulsar of 120 kyr (Abdo et al. 2010b). The large luminosity ratio might be natural for such an evolved PWN.

This cut-off hypothesis also explains the difference in size between the TeV and X-ray emissions, as discussed in Aharonian et al. (2005b). X-rays are emitted by young electrons, because higher energy electrons lose their energy quickly. On the other hand, older electrons radiate TeV γ-rays. Such a difference in age could cause the concentration of X-ray emission near the pulsar and the diffusion of TeV emission. Thus, the size of the X-ray emitting region could be much smaller than that of TeV.

4.3. Other Structures

The best-fit parameters of structure 2 are almost the same as that in structure 1. In addition, the X-ray emission size is also comparable to structure 1. Although no pulsar is found at the location of structure 2, the X-ray emission can be explained by PWN in the same manner as structure 1. If structure 2 is also a PWN, a part of the TeV emission could originate from this source.

The remaining diffuse emission also exhibits the same spectral shape as structure 1. However, the X-ray flux and the size are much larger than structures 1, 2. We cannot insist that the remaining flux is related to TeV emission only by the spectral similarities.

5. Summary

We observed the first unidentified TeV γ-ray source TeV J2032+4130 with Suzaku, and detected two structures of diffuse X-ray emission. The position of structure 1 is coincident with the GeV γ-ray pulsar. We also detected a hint of diffuse emission extended over the whole region of TeV emission. By estimating the contribution of point sources by Chandra, we extracted the X-ray spectra of the diffuse components. X-ray and TeV γ-ray emissions can be explained by...
electrons with a high-energy cut-off above the TeV region, which could originate in old PWN. Such an energy distribution of electrons may lead to a smaller X-ray emission size compared with TeV emission.

This research made use of data obtained from Data ARchives and Transmission System (DARTS), provided by Center for Science-satellite Operation and Data Archives (C-SODA) at ISAS/JAXA.

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