Suzaku Observation of HESS J1825−137: Discovery of Largely-Extended X-rays near from PSR J1826−1334

Hideki UCHIYAMA, Hironori MATSUMOTO, Takeshi Go TSURU, and Katsuji KOYAMA
Department of Physics, Graduate School of Science, Kyoto University, Sakyo-ku, Kyoto 606-8502
uchiyama@crscphys.kyoto-u.ac.jp

and

Aya BAMBA
Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency,
3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510

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Abstract

We observed the brightest part of HESS J1825−137 with the Suzaku XIS, and found diffuse X-rays extending at least up to 15′ (~17 pc) from the pulsar PSR J1826−1334. The spectra have no emission line, and are fitted with an absorbed power-law model. The X-rays, therefore, are likely due to synchrotron emission from a pulsar wind nebula. The photon index near at the pulsar (r ≤ 1.5′) is Γ = 1.7 while those in r = 1.5′ − 16′ are nearly constant at Γ = 2.0. The spectral energy distribution of the Suzaku and H.E.S.S. results are naturally explained by a combined process; synchrotron X-rays and γ-rays by the inverse Compton of the cosmic microwave photons by high-energy electrons in a magnetic field of ~ 7 μG. If the electrons are accelerated at the pulsar, the electrons must be transported over 17 pc in the synchrotron life time of 1900 yr, with a velocity of ≥ 8.8 × 10^3 km s^{-1}.

Key words: pulsars: individual (PSR J1826−1334 = PSR B1823−13) — ISM: individual (G18.0−0.7, HESS J1825−137)
emission via the synchrotron process. However, the VHE γ-rays are more extended than the X-rays. Furthermore, the X-rays have the electron origin (IC), the typical energy of electrons is ∼20 TeV. On the other hand, the typical energy of electrons emitting synchrotron X-rays is ∼100 TeV assuming a magnetic field of $B = 10 \mu G$. These apparent differences between X-rays and γ-rays may play a key role for the PWNe physics, such as the energy transport mechanism of and the history of energy injections to electrons.

The extent of the diffuse X-ray emission, however, may be underestimated, due mainly to the limited sensitivity XMM-Newton and Chandra for diffuse X-rays. We hence observed the PWN with the X-ray Imaging Spectrometers (Koyama et al. 2007) on board the Suzaku satellite (Mitsuda et al. 2007).

In this paper, we will introduce the observations in section 2, our analysis and results are explained in section 3, and we will discuss our results in section 4. Uncertainties are quoted at the 90% confidence range unless otherwise stated.

2. Observations and Data Reduction

We observed PSR J1826−1334 on 2006 October 17−19, with the field center at the VHE γ-ray peak of HESS J1825−137 (source region), and an offset position on 2006 October 19−20, where no VHE γ-ray has been detected (background region). The Galactic longitude of the background region was selected to be almost the same as that of the source region, so that the Galactic Ridge X-ray Emission (GRXE) at the source position can be reliably subtracted (e.g. Worrall et al. 1982; Warwick et al. 1985; Koyama et al. 1986; Yamauchi, Koyama 1993; Yamauchi et al. 1996; Kaneda et al. 1997; Sugizaki et al. 2001; Tanaka 2002; Ebisawa et al. 2005; Revnivtsev et al. 2006a; Ebisawa et al. 2008). The two observations are summarized in figure 1 and table 1.

Fig. 1. Suzaku field of view overlaid on the H.E.S.S. smoothed excess map, which is the same as figure 1 in Aharonian et al. (2006b). The scale is in units of integrated excess counts. We also show the position of PSR J1826−1334 (cross mark), the peak of the VHE γ-ray emission (white circle) and the regions from which we made radial profiles (thin line) in section 3.2.1

The observations were made with the X-ray Imaging Spectrometer (XIS) on the focal planes of four X-ray telescopes (XRT) onboard Suzaku. The XIS system consists of four CCD detectors (XIS 0, 1, 2, and 3). XIS 0, 2, and 3 have front-illuminated (FI) CCDs, while XIS 1 contains a back-illuminated (BI) CCD. A combination of the XIS and the XRT provides a spatial resolution of ∼ 2' in a half-power diameter (HPD) and a field-of-view (FOV) of 18' × 18'. Using the calibration sources ($^{55}$Fe), we confirmed that the energy resolution of the XIS was ∼ 210 eV at 5.9 keV. The details of Suzaku, the XIS, and the XRT are given in Mitsuda et al. (2007), Koyama et al. (2007), and Serlemitsos et al. (2007), respectively.

The XIS was operated in the normal clocking full window mode and the data of the two editing modes, 3 × 3 and 5 × 5, were combined. We used the processed data version 2.0.6.13 and the HEADAS software version 6.4. After removing the epoch of low-Earth elevation angles less than 5 degrees (ELV < 5°), the day earth elevation angle less than 20 degrees (DYE < 20°) and the South Atlantic Anomaly (SAA), the effective exposure times were about 50.3 ks and 52.1 ks for the source and background regions, respectively. Finally we removed flickering pixels and hot pixels using cleansis.

3. Analysis and Results

3.1. Background Region

In the background region, we found four point sources. The brightest source at $(\alpha, \delta) = (18^{h}27^{m}32^{s}, -13^{\circ}17^{m}41^{s})$ is recorded as a star in the Catalog of PSPC WGA Source of ROSAT (White et al. 2000). The other sources at $(\alpha, \delta) = (18^{h}27^{m}36^{s}, -13^{\circ}12^{m}36^{s}), (18^{h}27^{m}46^{s}, -13^{\circ}13^{m}22^{s})$, and $(18^{h}28^{m}04^{s}, -13^{\circ}11^{m}25^{s})$ are not found in any X-ray source catalogs.

Excluding the four source regions of a 1/8-radius circle, we made the background spectrum from the data obtained by each XIS sensor in a circular with a radius of 9'. The solid angle we extracted the spectra from is 212 arcmin$^2$. The Non-X-ray background (NXB) spectrum of each sensor was made from the NXB database of the same region in the detector coordinate (DETX/Y), sorted by the geomagnetic cut-off rigidity (COR) to become the same COR distribution of the background observation ($\times \text{nxxbgen}$). This sorting process improves the reproducibility of the NXB spectrum up to < 4% accuracy (in detail, see Tawa et al. 2008). We then subtracted the NXB spectrum from the background spectrum. Since the gains and responses of the FIs are almost the same, we averaged the spectra of the three FIs. The background spectra are shown in figure 2.

We fitted the spectrum (figure 2) with a model consists of a thin thermal plasma component (APEC; Smith et al. 2001) and the Cosmic X-ray Background (CXB) component. The fitting were made for the FI and BI spectra simultaneously. The detector responses (RMF) and telescope responses (ARF) generated by $\times \text{isrmfgen}$ and $\times \text{issinarfgen}$ (Ishisaki et al. 2007) were averaged for the three FIs with addrmf and addarf. Since the CXB was not subtracted from the spectrum, we added the CXB model spectrum in the fitting, assuming a

1 We used the image fits file of the H.E.S.S. website at http://www.mpi-hd.mpg.de/hfm/HESS/public/publications/HESSJ1825II_Fig1.fits.

2 http://heasarc.gsfc.nasa.gov/W3Browse/rosat/wgacat.html
power-law of photon index 1.4 with the intensity of 5.4 × 10⁻¹⁵ erg s⁻¹ cm⁻² arcmin⁻² (2–10 keV) (Kushino et al. 2002). The absorption for the CXB is the Galactic H I column density towards the background region of ∼ 1.1 × 10²² cm⁻² (Kalberla et al. 2005), plus that of molecular hydrogen of ∼ 2 × 10²² cm⁻² (Dame et al. 2001). Then the overall column density for the CXB (N_H^{CXB}) is N_H^{total} = N_H + 2N_II = 5 × 10²² cm⁻². For a thin thermal plasma, the column density, temperature, metal abundances, and normalization were free parameters. The cross section of the photoelectric absorption and the solar abundance of each element were obtained from Morrison & McCammon (1983) and Anders, Grevesse (1989).

This model, however, is rejected with χ²/d.o.f. = 1117.1/280. A model of two-temperature plasma plus the CXB was also rejected (χ²/d.o.f. = 609.9/277) with a large residual at 0.56 keV, which is attributable to the O VII Kα line. We then fitted the spectra with three-temperature plasma plus the CXB model, where the abundances in each plasma were assumed to be the same. The fit was improved to be χ²/d.o.f. = 371.1/274, but still large residuals were seen in Ne X, S XV and Ar XVII Kα lines. Then we relaxed the abundances of Ne, S and Ar to be free, and the fit was acceptable with χ²/d.o.f. = 310.5/271.

The main component of this spectrum is thought to be the GRXE. An Fe I Kα line is reported in the GRXE (Ebisawa et al. 2005). Although the soft component has the same temperature as the local hot bubble, the absorption column is larger than the local hot bubble, and similar to that of the medium component of ∼ 10²² cm⁻². Thus the soft component may have a comparable distance of the low-temperature component of the GRXE, and hence may comprise additional component of the GRXE. To confirm the same distance, we tried a model with a common N_H for the soft and medium-temperature components. This model was acceptable with χ²/d.o.f. = 310.3/271. The common N_H is 0.81 ± 0.06 × 10²² cm⁻².

In the 0.8–10 keV band, the contribution of the low-temperature component is only 4%, we hence used the model GRXE spectrum as being the medium and high components, at least above 0.8 keV.

### Table 1. Log of Suzaku observations.

| Region       | Target coordinate (R.A., Dec.) | Obs. start time | Obs. end time | Effective exp. (ks) |
|--------------|--------------------------------|-----------------|---------------|---------------------|
| Source       | (18°26′00″, -13°41′42″)        | 2006/10/17 19:37:16 | 2006/10/19 04:02:15 | 50.3               |
| Background   | (18°27′36″, -13°15′36″)        | 2006/10/19 04:03:16 | 2006/10/20 12:10:25 | 52.1               |

*Equinox in J2000.

### Table 2. Result of the spectrum fitting of the background region with the model of thin thermal three-temperature plasma with an Fe I Kα line plus the CXB.

|                | Soft          | Medium        | High          |
|----------------|---------------|---------------|---------------|
| N_H (10²² cm⁻²) | 0.61 ± 0.21   | 0.84 ± 0.09   | 1.19 ± 0.25   |
| kT (keV)       | 0.11 ± 0.03   | 0.50 ± 0.03   | 4.76 ± 0.55   |
| f_0.8–10^°(10⁻¹³) | 1.8 (10) | 8.4 (47)   | 30 (44)       |
| Abundance (solar) | Ne          | S             | Ar            |
|                 | 0.57 ± 0.19  | 1.27 ± 0.33   | 2.10 ± 0.39   |
|                 | others       | 0.33 ± 0.07   |               |
| f_6.4 (10⁻¹⁶)  | 3.5 ± 2.0    |               |               |
| χ²/d.o.f.      | 302.8/270    |               |               |

* Observed flux in the 0.8–10 keV band in the unit of erg s⁻¹ cm⁻². Values in parentheses are the absorption corrected values.
† Observed photon flux of 6.4 keV line in the unit of photons s⁻¹ cm⁻².

**Fig. 2.** Spectra of the background region. The best-fit result of the model of thin thermal three-temperature plasma with an Fe I Kα line plus the CXB is also shown. Black and red data show the FI and BI spectra, respectively. The vertical error bars of each data point are the 1σ error. The best-fit models for FIs and BI are shown with solid and broken lines, respectively. In this model, the soft, medium- and high-temperature components correspond to the GRXE. The power-law component corresponds to the CXB. The yellow line shows an Fe I Kα line.
3.2. Source Region

3.2.1. Image

The image of the source region was made with the vignetting correction (\textit{xissim}; Ishisaki et al. 2007) after the NXB subtraction. Figure 3 shows the 3-FI images of the source region in the 1–3 keV and 3–9 keV bands.

Among the five bright point-like sources in figure 3, four are identified in the XMM-Newton serendipitous source catalogue (2XMM)\(^4\): 2XMM J182557.9–134755, 2XMM J182620.9–134426, 2XMM J182617.1–134111 and 2XMM J182629.5–133648. Referring the accurate position of these XMM-Newton sources (\(\leq 1\)\(^\prime\))\(^5\), we corrected the coordinates of XIS images by shifting 24\(^\prime\) to match the source positions with each other. After this correction, the position of the brightest peak in figure 3 coincides with PSR J1826–1334. The coordinate of the point source not cataloged by XMM-Newton (source 5 in figure 3) is \((\alpha, \delta)_{2000} = (18h26m12s, -13^\circ48^\prime33^\prime\prime)\) after the correction.

Although XMM-Newton (Gaensler et al. 2003) and Chandra (Pavlov et al. 2008) resolved the extended emission around PSR J1826–1334 into the core and diffuse components, the XIS could not resolve due to the limited spatial resolution. We, instead, found that the diffuse emission is largely extended beyond 5\(^\prime\), which is the radius previously reported.

In order to study the spatial distribution of the diffuse component, we made the radial profile of the surface brightness in the 1.0–9.0 keV band. The origin of the profile is at the pulsar point, and the data area of the profile is shown in figure 1. Fluxes of the five point sources in the circles of 1.8\(^\prime\) radius were removed (figure 3).

For comparison, we also made the radial profile in the same detector area of the background region with the same process as the source profile (see figure 1). These two profiles are shown in figure 4. The surface brightness of the source region is clearly larger than that of the background region.

3.2.2. Spectrum

We made X-ray spectra from the four regions designated as A, B, C, and D in figure 3. Like the radial profile, we removed the data of the five point sources. The region A is a circle of 1.5\(^\prime\)-radius centered on PSR J1826–1334. Region A includes the core region, while region B corresponds to the diffuse region, both are reported by Gaensler et al. (2003). Regions C and D are new diffuse X-ray area discovered by this Suzaku observation.

The spectra were made with the same process as the background region, and subtracted the background spectrum shown in figure 2. In the background subtraction, we took into account the difference of the vignetting between the regions A–D and the background region. The background-subtracted spectra are shown in figure 5.

Since the spectra have featureless with no emission line, we fitted the spectra with an absorbed power-law model. Free parameters are the normalization, photon index (\(\Gamma\)), and \(N_H\). The fits are acceptable with the best-fit results shown in figure 5 and table 3.

\(^4\) http://xmmssc-www.star.le.ac.uk/Catalogue/2XMM/

\(^5\) We referred to XMM-Newton Users’ Handbook, available at http://xmm.vilspa.esa.es/external/xmm_user_support/documentation/uhb_2.5/index.html.

Fig. 3. XIS images of the source region in the 1.0–3.0 keV (a) and 3.0–9.0 keV (b) bands in the Galactic coordinate. The NXB was subtracted and the vignetting was corrected. These images were smoothed using a Gauss function with \(\sigma = 0.2\)\(^\prime\). The scale is in units of photons. A corner illuminated by the calibration source was removed. The peak position of the VHE \(\gamma\)-ray emission is shown with the white circle. The source regions of spectra (regions A, B, C and D) are shown with the green lines. The cyan circles with diagonal lines (1–5) are the point-like source regions excluded from the analyses of the spectra and the radial profile. The sources 1–4 are cataloged by XMM-Newton.
Table 3. Best-fit results of the regions A, B, C and D.

| Region | $\Omega$ | $N_H$ ($10^{22}$ cm$^{-2}$) | $\Gamma$ | Norm.$^3$ ($10^{-4}$) | $f_{0.8-10}$ ($10^{-12}$) | $\chi^2$/d.o.f. |
|--------|---------|----------------|---------|----------------|-----------------|----------------|
| A      | 7.07    | $1.11^{+0.14}_{-0.15}$ | $1.69^{+0.07}_{-0.07}$ | $3.0^{+0.5}_{-0.5}$ | 1.3 (1.7) | 65.1/61 |
| B      | 21.4    | $0.98^{+0.11}_{-0.12}$ | $1.97^{+0.09}_{-0.10}$ | $4.2^{+0.6}_{-0.7}$ | 1.2 (1.7) | 104.6/84 |
| C      | 39.8    | $0.91^{+0.12}_{-0.11}$ | $2.01^{+0.10}_{-0.10}$ | $4.4^{+0.7}_{-0.7}$ | 1.2 (1.7) | 105.0/100 |
| D      | 76.3    | $0.86^{+0.14}_{-0.15}$ | $1.94^{+0.12}_{-0.08}$ | $4.5^{+0.8}_{-0.8}$ | 1.4 (1.9) | 111.1/113 |

$^*$ The regions are shown in figure 3.
$^†$ Solid angle of the region ; arcmin$^2$.
$^‡$ Photon index of the power-law model.
$^§$ Normalization of the power-law model ; photons keV$^{-1}$ s$^{-1}$ cm$^{-2}$ at 1 keV.
$^l$ Observed flux in the 0.8–10 keV band in the unit of erg s$^{-1}$ cm$^{-2}$. Values in parentheses are the absorption corrected values.

Fig. 5. Spectra of the regions A, B, C and D with the best-fit models. Black and red data show the spectra of the FI and BI, respectively. The vertical error bars of each data point are the 1$\sigma$ error.
thin thermal plasma of solar abundance contributes, at most, an abundance of less than 0.15 solar. We hence can say that the thermal model of solar abundance. This model is rejected if any, in the extended region, would be the shock heated interstellar gas. We therefore fitted the spectrum with a thin thermal component. Most probable thermal plasma, which contains thermal component. The best-fit parameters of these fitting are shown in table 2. No such line/absorption structures are found in the spectra of the regions B, C, and D given in figure 2.

The power-law index of the region A is \( \Gamma = 1.7 \), which is harder than the other 3 regions. The regions B, C and D show almost the same photon indices of \( \Gamma = 2.0 \) and the same interstellar absorptions of \( N_H \sim 1 \times 10^{22} \) cm\(^{-2} \). We therefore added these 3 spectra, and examined whether the spectrum contains thermal component. Most probable thermal plasma, if any, in the extended region, would be the shock heated interstellar gas. We therefore fitted the spectrum with a thin thermal model of solar abundance. This model is rejected with \( \chi^2/\text{d.o.f.} = 547.0/301 \). Then we relaxed the abundance to be free, and found that the model becomes acceptable with \( \chi^2/\text{d.o.f.} = 341.8/300 \). However we need an unrealistically low abundance of less than 0.15 solar. We hence can say that the thin thermal plasma of solar abundance contributes, at most, only 15% in the 0.8–10 keV flux of the largely extended emission. The best-fit parameters of these fitting are shown in table 4.

4. Discussion

4.1. Radial Profile

In figure 4, we see largely extended emission up to 15′ for the first time. The radial profile becomes flat beyond 10′. The flux in this flat region is 50% larger than the mean flux of the background region. One may argue that the difference could be due to the fluctuations of the NXB, CXB and GRXE. We therefore discuss whether any systematic errors of the background subtraction (NXB, CXB and GRXE) may mimic such excess.

The reproductively of the NXB is extensively examined by Tawa et al. (2008). Using the same method, the NXB reproductively in the 1.0–9.0 keV band at the 99% confidence level is less than \( 2.2 \times 10^{-5} \) counts s\(^{-1}\) arcmin\(^{-2}\). This uncertainty is very small compared with the excess level of the radial profile of the source region (figure 4).

The fluctuation of the CXB in the XIS FOV is estimated to be \( \sim 36\% \) at the 99% confidence level with the same way as Tawa et al. (2008). Since the CXB flux is only 10% of the background spectrum, the overall uncertainty is less than 4%.

The largest uncertainty would come from the subtraction of the GRXE. Yamauchi, Koyama (1993) and Kaneda et al. (1997) reported that the GRXE has a large scale structure depending on the galactic longitude (l) and latitude (b). The l-dependency is rather null in this region hence can be neglected in our case. The b-dependency is expressed by the scale height of the medium and hard components given by 2 and 0.7 degrees, respectively (Yamauchi, Koyama 1993; Kaneda et al. 1997). Since the flux of the medium and hard components in our region is nearly the same in the 1.0-9.0 keV band, we can estimate that GRXE flux at the source position is about 20% larger than that in the background position.

The most unknown factor is a possible fluctuation of the GRXE from position to position, which may cause under/over subtraction of the GRXE. If there is under/over subtraction of the GRXE, the source spectra should have emission/absorption line structures at the Si, S and Fe K-shell transition energies, because the GRXE has strong lines of these elements (see figure 2). No such line/absorption structures are found in the spectra of the regions B, C, and D given in figure 5, which supports that the GRXE is properly subtracted. We further checked possible under/over subtraction of the GRXE by fitting the source spectrum (combined B+C+D) with a model of absorbed power-law + \( \Delta \times \) GRXE, where the spectral parameters of the GRXE, other than normalization (\( \Delta \)) were fixed to the best-fit values given in table 2. As a result, we can set the 90% upper-limit of the possible contamination of the GRXE to be 1.5% of the excess flux. Accordingly, the largely extended power-law component from the source region is real, not an artifact of improper GRXE subtraction.

4.2. Comparison with earlier X-ray observation

In the XMM-Newton observation, Gaensler et al. (2003) reported that the photon indices of the core and diffuse components are \( \sim 1.6 \) and \( \sim 2 \), respectively. Since the region A includes both the components, our result of \( \Gamma \sim 1.7 \) is reasonable.

From the region B, we determined more accurate photon index and interstellar absorption than the diffuse component of XMM-Newton. Moreover, we detected the X-ray emission farther out of the previously reported region. The peak position of the extended emission coincides with the pulsar PSR J1826–1334, and the surface brightness decreases with the distance from the pulsar. The major fraction of the extended emission cannot be a thin thermal plasma of the SNR, but is non-thermal origin. The photon indices are smaller than the canonical value of synchrotron emissions found in non-thermal SNRs (2.5–3.0; Bamba et al. 2005). Furthermore, the morphology of the extended emission is different from limb-brightened structures such as SN1006 (Koyama et al. 1995). Thus the ex-

![Figure 4: Radial profile of the surface brightness per 1 FI CCD in the 1.0-9.0 keV band. The NXB was subtracted and the vignetting was corrected. The vertical error bar of each data point is the 1σ error. The position of the peak of VHE γ-ray emission is shown by a vertical broken line.](image-url)

**Table 4.** Best fit parameters of the fittings of the combined spectra of the region B–D with different models.

| Model | Power law | APEC | APEC |
|-------|-----------|------|------|
| 1/\(kT\) (keV) | 1.98\(^+0.06\)\(^{-0.06}\) | 13\(^+2\)\(^{-2}\) | 6.4\(^+0.7\)\(^{-0.7}\) |
| \(N_H\) (\(10^{22}\) cm\(^{-2}\)) | 0.93\(^+0.06\)\(^{-0.06}\) | 0.47\(^+0.03\)\(^{-0.03}\) | 0.70\(^+0.05\)\(^{-0.05}\) |
| \(\chi^2/\text{d.o.f.}\) | 326.0/301 | 547.0/301 | 341.8/300 |

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tended emission cannot be explained as non-thermal emission from shell-like SNR. The photon indices are close to typical values of PWNe (Gaensler & Slane 2006). Therefore, we conclude that the extended emission is synchrotron radiation from a PWN, as suggested first by Gaensler et al. (2003).

Our results indicate that the PWN extends over 15′, which corresponds to $17d_{\text{4kpc}}$ pc, where $d_{\text{4kpc}}$ is the distance of PSR J1826–1334 normalized by 4 kpc. The interstellar absorption of $N_H \sim 10^{22}\text{cm}^{-2}$ is consistent with the distance of $\sim 4$ kpc obtained by the radio measurements (Taylor & Cordes 1993; Cordes & Lazio 2002). The extent of $\sim 17d_{\text{4kpc}}$ kpc is larger than typical X-ray PWNe; for example, one of the largest PWNe is 3C58, where the X-ray nebula extends up to $\sim 6$ pc from the pulsar (Slane et al. 2004).

The total X-ray luminosity ($L_X$) from the regions A–D is $8.6d_{\text{4kpc}}^2 \times 10^{33}$ erg s$^{-1}$ in the 2–10 keV band. The ratio of $L_X$ to the spin-down luminosity is not unusual compared with other PWNe (Cheng et al. 2004; Li et al. 2007).

4.3. Comparison with γ-ray observation

Since the region C overlaps the bright region of the VHE γ-rays, we can make a reliable spectral energy distribution (SED) between the X-rays and the VHE γ-rays for the first time. In figure 6, we show the X-ray SED of the region C and the γ-ray SED of the brightest region (Radius 0′:15 in table 2 of Aharonian et al. 2006b).

If the origin of the VHE γ-rays is the inverse Compton scattering of the CMB photons by high-energy electrons, these electrons should emit synchrotron radiation. We also plot the estimated synchrotron intensity in the magnetic fields of $B = 10$, 5, 1 μG. In the case of $B \sim 7$ μG, the estimated synchrotron intensity smoothly connects to the X-ray intensity. Thus both the X-rays and VHE γ-rays can be explained by high-energy electrons of a single population in a magnetic field of $B \sim 7$ μG, approximately the same as the core region of $B \sim 10$ μG (Gaensler et al. 2003).

According to de Jager & Djannati-Atai (2008), required electron energy $E_e$ in a magnetic field $B$ to radiate synchrotron photons of mean energy $E_{\text{syn}}$ is given by $E_e = 120$ TeV ($B/7\mu\text{G}$)$^{-1/2}(E_{\text{syn}}/2\text{keV})^{1/2}$. On the other hand, the mean electron energy $E_e$ required to inverse Compton scatter the CMB photons to energies $E_{\text{IC}}$ is typically $E_e = 18$ TeV ($E_{\text{IC}}/1\text{TeV})^{1/2}$ (de Jager & Djannati-Atai 2008). Thus electrons responsible for X-rays have larger energies than those for VHE γ-rays.

The peak position of the VHE γ-rays does not coincide with the pulsar (Aharonian et al. 2006b), while the peak position in X-rays are consistent with the pulsar. There is no indication of the γ-ray peak in the XIS images (figures 3 and 4). The offset is a mystery, and the reason is not yet clarified. However, as Pavlov et al. (2008) mentioned, the local excess of the seed photons for the inverse Compton scattering created by the near hidden star might cause the offset. In this case, a magnetic field stronger than $\sim 10$ μG might be required.

Hartman et al. (1999) reports an EGRET source 3 EG J1826–1302 in the north of PSR J1826–1334, and the relation between them has been discussed by some authors (e.g. Zhang, Chen & Fang 2008). The EGRET source is however, out of the FOV of the XIS in our observation. Thus direct comparison between the intensities of the EGRET source and the X-ray we found is impossible, and the relation between them is not clarified.

4.4. Widely extended PWN

Except for the neighborhood of the pulsar, the photon index is constant at $\Gamma = 2.0$ from the pulsar to 15′. The smooth decay of the intensity with the distance from the pulsar shown in figure 4 suggests that the accelerator is the pulsar itself. This means the high-energy electrons should be transported over $17d_{\text{4kpc}}$ pc within its synchrotron life time. According to de Jager & Djannati-Atai (2008), the synchrotron life time of an electron emitting photons of mean energy $E_{\text{syn}}$ in an isotropic magnetic field of the strength $B$ is $\tau_{\text{syn}} = 1.9\text{kyr} (B/7\mu\text{G})^{-3/2}(E_{\text{syn}}/2\text{keV})^{1/2}$. Thus, the velocity for transporting the high-energy electrons should be more than $17d_{\text{4kpc}}$ pc/τ$_{\text{syn}} \sim 8.8 \times 10^3$ km s$^{-1}d_{\text{4kpc}}(B/7\mu\text{G})^{3/2}(E_{\text{syn}}/2\text{keV})^{1/2}$.

A simple transport mechanism is diffusion by a magnetic field or convection. In the case of diffusion, our results indicate that the diffusion coefficient is $D = R^2/(2\tau) = 2.3 \times 10^{28} \text{cm}^2\text{s}^{-1}(R/17\text{pc})^2(\tau/1.9\text{kyr})^{-1}$, where $R$ is the size of the extended emission, and $\tau$ is the transport time for which we assume the synchrotron life time.

We can express the mean free path of the electron in a magnetic field $B$ as $\lambda_{\text{F}}$, where $\lambda_{\text{F}} = E_e/(eB)$ is the gyro radius of an electron with energy $E_e$ and charge $e$, and the parameter $\lambda_{\text{F}}$ characterizes the efficiency of diffusion. Then the diffusion coefficient can also be expressed as $D \sim \lambda_{\text{F}}^2/e = 2.3 \times 10^{28} \text{cm}^2\text{s}^{-1} (B/7\mu\text{G})^{-1}(E_e/120\text{TeV})/f(40)$. Thus, our results suggest $f \sim 40$. According to de Jager & Djannati-Atai (2008), $f$ should be $\leq 1$ in perpendicular diffusion. Therefore, our results suggest that the transport mechanism is not the perpendicular diffusion, but it might be diffusion parallel to the magnetic field or convection.

Collisions between a PWN and a reverse shock from the

![Fig. 6. Spectral energy distribution of the extended component from the X-ray to TeV γ-ray bands. The intensity of the region C in table 3 and that of the radius 0′:15 region in table 2 of Aharonian et al. (2006b) are used for X-ray and VHE γ-ray. The synchrotron radiation from the electrons responsible for VHE γ-ray (0.25–10 TeV) is plotted toward the left for three different values of the magnetic field.](image-url)
surrounding SNR were proposed as a scenario to explain the morphology of one-sided PWNe (Pavlov et al. 2008), such as Vela pulsar (Blondin, Chevalier & Frierson 2001; Gaensler et al. 2003). Whether or not this scenario can explain the large extent of \( \sim 17d_{\text{pc}} \) pc and the smooth radial profile shown in figure 4 is an open problem.

5. Summary

- We observed the peak position of HESS J1825−137 with the Suzaku XIS, and found diffuse X-ray emission extended at least up to \( 15' \), corresponding to 17 pc.
- The spatially-resolved X-ray spectra have no emission line, and can be fitted with an absorbed power-law model. Therefore the X-rays are likely to be synchrotron emission from a pulsar wind nebula. Except for the neighborhood of the pulsar, the photon indices are spatially constant at \( \Gamma = 2.0 \).
- The SED of the X-ray and the VHE \( \gamma \)-rays is made from the same region, which can be explained by high-energy electrons of a single population in a magnetic field of \( B \sim 7 \mu G \).
- All the facts indicate that electrons of energy \( \sim 120 \) TeV are distributed over 17 pc. If the acceleration site of the electrons is the pulsar, the electrons should be transported over the distance within its synchrotron lifetime. This condition requires that the transportation velocity is at least \( 8.8 \times 10^3 \) km s\(^{-1}\), which may be explained by diffusion perpendicular to the magnetic field.

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