Measuring the Broad-band X-Ray Spectrum from 400 eV to 40 keV in the Southwest Part of the Supernova Remnant RX J1713.7−3946

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Abstract

We report on results from Suzaku broadband X-ray observations of the southwest part of the Galactic supernova remnant (SNR) RX J1713.7−3946 with an energy coverage of 0.4–40 keV. The X-ray spectrum, presumably of synchrotron origin, is known to be completely lineless, making this SNR ideally suited for a detailed study of the X-ray spectral shape formed through efficient particle acceleration at high speed shocks. With a sensitive hard X-ray measurement from the HXD PIN on board Suzaku, we determine the hard X-ray spectrum in the 12–40 keV range to be described by a power law with photon index $\Gamma = 3 \pm 0.2$, significantly steeper than the soft X-ray index of $\Gamma = 2.4 \pm 0.05$ measured previously with ASCA and other missions. We find that a simple power law fails to describe the full spectral range of 0.4–40 keV and instead a power-law with an exponential cutoff with hard index $\Gamma = 1.50 \pm 0.09$ and high-energy cutoff $\epsilon_c = 1.2 \pm 0.3$ keV formally provides an excellent fit over the full bandpass. If we use the so-called SRCUT model, as an alternative model, it gives the best-fit rolloff energy of $\epsilon_{\text{roll}} = 0.95 \pm 0.04$ keV. Together with the TeV $\gamma$-ray spectrum ranging from 0.3 to 100 TeV obtained recently by HESS observations, our Suzaku observations of RX J1713.7−3946 provide stringent constraints on the highest energy particles accelerated in a supernova shock.

Key words: acceleration of particles — ISM: individual(RXJ 1713.7−3946) — ISM: supernova remnants — X-rays: ISM

1. Introduction

Over the past decade, the spectral and spatial properties of non-thermal X-ray emission, presumably synchrotron radiation by multi-TeV electrons, in young shell-type supernova remnants (SNRs) have been extensively studied with X-ray satellites, especially with ASCA and Chandra, providing observational support for the general picture that Galactic cosmic rays are sustained by strong shocks in SNRs (Koyama et al. 1995; Slane et al. 1999; Gotthelf et al. 2001; Hwang et al. 2002; Uchiyama et al. 2003; Long et al. 2003; Bamba et al. 2003; Warren et al. 2005). An excellent example comes from Chandra observations of the Tycho’s SNR, where the remnant is delineated by a thin (1о or less) layer of X-ray synchrotron emission that exhibits spectral steepening behind the shock (Cassam-Chenaı et al. 2007). This strongly indicates that TeV-scale electrons are indeed accelerated at the outer blast wave. The well developed theory of diffusive shock acceleration (for reviews, see Blandford & Eichler 1987; Malkov & Drury 2001) provides a basic framework for our understanding of cosmic-ray acceleration in collisionless SNR shocks, though some key ingredients in the theory, especially the generation of magnetohydrodynamic (MHD) waves and their interactions with cosmic-ray particles (Bell & Lucek 2001; Bell...
X-ray observations of shell-type SNRs can in principle probe the “microphysics” of the shock acceleration process; the development of MHD waves can be explored by measuring the energy of the spectral cutoff that is regulated by the acceleration rate, which, in turn, is determined by the shock velocity and the energy density of stochastic magnetic fields relative to ordered fields. In previous work, it has been presumed that the nonthermal X-ray remnant made with H.E.S.S. with a 1–10 TeV flux of $3.5 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, which is not exceeded by any other shell-type SNR. This was the first SNR to be confirmed as a TeV $\gamma$-ray source using ground-based Cherenkov telescopes by two groups, CANGAROO (Muraiishi et al. 2000; Enomoto et al. 2002) and H.E.S.S. (Aharonian et al. 2004; Aharonian et al. 2006; Aharonian et al. 2007). Detections of TeV $\gamma$-rays distributed over the entire remnant made with H.E.S.S. with a 1–10 TeV flux of $3.5 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, make this object well suited for exploring cosmic-ray acceleration in shell-type SNRs. The spectacular H.E.S.S. $\gamma$-ray image with spatial resolution of a few arc-minutes appears generally quite similar to the X-ray image, suggesting an intimate physical connection between the nonthermal X-rays and TeV $\gamma$-rays.

Due to its faintness in the radio band, the remnant eluded detection in early radio surveys and was only discovered thanks to X-ray observations during the ROSAT All-Sky Survey (Pfeffermann & Aschenbach 1996). ASCA revealed intense synchrotron X-ray emission in the northwestern (NW) part of the remnant (Koyama et al. 1997). The spectrum here is best-fitted by a power law of photon index $\Gamma = 2.4 \pm 0.1$ with interstellar absorption $N_{\text{H}} = (0.81 \pm 0.06) \times 10^{22}$ cm$^{-2}$, and is widely presumed to be synchrotron in nature. Diffuse synchrotron X-ray emission appears to be distributed over the entire face of the SNR with similar index ($\Gamma \simeq 2.3 \pm 0.2$) and without measurable thermal X-ray emission (Slane et al. 1999). Faint synchrotron radio emission was detected in RX J1713.7–3946, especially toward the western shell (Slane et al. 1999; Lazendic et al. 2004). With Chandra observations, it was found that the brightest part of the northwest X-ray shell consists of a complex network of bright filaments and knots embedded in more diffuse emission (Uchiyama et al. 2003). The X-ray spectra of various components in the NW rim are similar to each other and well fit by a power-law function with $\Gamma \simeq 2.1–2.5$ (Uchiyama et al. 2003; Lazendic et al. 2004). Similar spatial and spectral characteristics were found in the southwestern (SW) rim as well based on $\text{XMM-Newton}$ data (Cassam-Chenai et al. 2004; Hiraga et al. 2005).

A nearby molecular cloud at $\sim 1$ kpc is likely associated with RX J1713.7–3946, based on high sensitivity CO observations made with the NANTEN telescope (Fukui et al. 2003; Moriguchi et al. 2005). The association between the molecular cloud at $\sim 1$ kpc and the X-ray remnant is suggested by their close morphological match as well as by the detection of broad-line CO emission (Fukui et al. 2003). This is further strengthened by a detailed comparison between the X-ray and molecular emissions (Uchiyama et al. 2005). The atomic and molecular hydrogen column density as a function of distance along the line-of-sight to the SNR reaches a value matching the X-ray absorbing column density at a distance of $\sim 1$ kpc (Koo et al. 2004), thus providing independent support for an association with the nearby (1 kpc) molecular cloud. With this distance, the guest star that appeared in A.D. 393 possibly corresponds to the supernova explosion from which SNR RX J1713.7–3946 originated (Wang et al. 1997). This association would make the remnant 1600 yr old. With this assumption, an X-ray point source (without an optical/radio counterpart) near the center of the remnant, 1WGA J1713.4–3949, is thought to be an associated neutron star (Slane et al. 1999; Lazendic et al. 2003), indicating a core-collapse supernova. It has been suggested (Slane et al. 1999; Ellison et al. 2001) that the supernova explosion occurred within the wind-blown bubble created by the massive progenitor star. We take the distance to SNR RX J1713.7–3946 to be 1 kpc in this paper.

Here we report on a wide band X-ray observation from 0.4 to 40 keV of the SW part of RX J1713.7–3946 made with the Suzaku satellite. The high sensitivity in the 12–50 keV band offered by the Hard X-ray Detector (HXD) on board Suzaku together with the X-ray Imaging Spectrometer (XIS) in the 0.4–12 keV band, allow us to measure for the first time the detailed spectral shape of the nonthermal X-ray emission from a supernova remnant. Since this is the first clear example of detecting extended hard X-ray emission with the HXD, we performed an in-depth analysis of the hard X-ray measurements. In Section 2, we describe the observations and methods of obtaining the data sets. In Section 3, we explain the analysis procedures to extract spectra and present spectral fitting for each of the HXD and XIS in turn. We then proceed with the implementation of HXD+XIS simultaneous modeling. We discuss the broadband X-ray spectrum in terms of the theory of diffusive shock acceleration in Section 4.
2. Observation and Data Reduction

We observed the southwestern (SW) part of RX J1713.7−3946 with Suzaku on 2005 September 26 (in the Performance Verification phase) for a total on-source duration of about 60 ks. The brightest portion of the remnant is its northwest shell, which lies nearly on the Galactic plane, where we were concerned that an unexpected transient source could appear and contaminate the HXD field of view. We therefore chose the second brightest part, i.e., the SW, to attempt a secure measurement of hard X-ray emission with the HXD. The X-ray Observatory Suzaku (Mitsuda et al. 2007), developed jointly by Japan and the US, has a scientific payload consisting of two kinds of co-aligned instruments, the XIS (Koyama et al. 2007) and HXD (Takahashi et al. 2007; Kokubun et al. 2007). The non-imaging HXD covers the hard X-ray bandpass of 10–600 keV with PIN silicon diodes (10–60 keV) and GSO scintillator (40–600 keV), both located inside an active BGO shield. We here make use of spectral data from the PIN diodes. The low background of the HXD PIN enables us to study high energy emission from RX J1713.7−3946 up to several tens of keV. Additionally, a narrow FOV of ∼25′ × 25′ (FWHM), which is defined by passive shields inserted in the BGO well-type collimator above the PIN diodes, is better suited to the study of extended emission in comparison with previous missions having larger FOVs. The XIS consists of four X-ray imaging CCD cameras covering a FOV of 17′8 × 17′8; three are front-illuminated (FI: 0.4–12 keV), one is back side illuminated (BI: 0.2–12 keV), and all have good energy resolution of ∼130 eV at 6 keV.

The observation log for our observations is shown in Table 1. In order to estimate possible contributions from diffuse emission along the Milky Way in the hard 10–60 keV band, we observed two nearby regions in which no apparent hard X-ray point sources exist (off-pointings, OFF1 and OFF2). The three fields of view are depicted in Figure 1, overlaid on the ASCA GIS image (1–5 keV) taken from Uchiyama et al. (2005). More recently, one year after the PV phase observations discussed here, we have covered almost the entire remnant using 10 separate pointings during the Suzaku AO-1 period. These results will be published elsewhere (Tanaka et al., in preparation).

We used data products made with version 1.2 of the pipeline processing. For the XIS analysis, we retrieved “cleaned event files” which were screened with standard event selections. We further screened the events with the following criteria: (1) cut-off rigidity larger than 8 GV and (2) elevation angle from the Earth rim larger than 10°. For HXD data, “uncleaned event files” were screened with standard event screening criteria. We excluded events during SAA passages and Earth occultation, and also those with cut-off rigidity less than 8 GV. The effective exposure times after these screenings are shown in Table 1. In this paper, data analysis was performed with HEADAS 6.0.1. 

3. Analysis

3.1. HXD Data Analysis

The HXD PIN achieves the lowest background level among all previous hard X-ray instruments (Kokubun et al. 2007). Also, a rather narrow FOV defined by a passive collimator suppresses contamination from nearby discrete sources and diffuse emission such as the Galactic ridge emission (Valinia & Marshall 1998) and the Cosmic X-ray background (CXB). However, even for a bright object like this target, the PIN spectrum is still exceed by the background — time-variable instrumental background induced in one way or another by cosmic-rays and trapped charged particles in orbit. The HXD instrument team has developed an effective method (Watanabe et al. 2007) of modeling the time-dependent non-X-ray background (NXB) by making use of the PIN upper discriminator (UD) signal that monitors passing charged particles through the silicon PIN diode. The background spectrum is generated based on a database of NXB observations accumulated to date during night- and day-earth observations. Note that in our analysis the background spectral model was generated with 100 times the actual number of background counts in order to minimize the photon noise on the background. The current NXB model is shown to be accurate within ∼5% (Mizuno et al. 2006). In Figure 2, we show the light curve of the raw count rate in the 12–40 keV range as a function of time for the on-source obs-
Table 1. Summary of the Suzaku observations of RX J1713.7−3946

| Pointing      | Obs. ID      | Coord. (J2000)          | Exposure | Date       |
|---------------|--------------|-------------------------|----------|------------|
| RX J1713.7−3946 SW | 100026010   | 17°12′17.0″, −39°56′11″ | 55/48    | 26/9/2005  |
| OFF1          | 100026020    | 17°09′31.9″, −38°49′24″ | 28/24    | 25/9/2005  |
| OFF2          | 100026030    | 17°09′05.1″, −41°02′07″ | 28/28    | 28/9/2005  |

Fig. 2. HXD PIN lightcurves in the 12–40 keV energy band. The black, red, and green points show the raw, background (NXB + CXB), and background-subtracted data, respectively. The NXB curve is constructed with the background model of Watanabe et al. (2007). The background-subtracted count rate is almost constant within statistical errors, as expected for the extended object like this, except for high background periods.

Fig. 3. Hard X-ray spectrum of the southwest part of RX J1713.7−3946 recorded with the HXD PIN. The data points in black show the raw spectrum, red points represent the background model (NXB+CXB), and green points are the background-subtracted spectrum.

\[
\frac{dN}{d\epsilon} = 7.9e^{-1.29\epsilon_{\text{keV}}} \cdot \epsilon_{\text{keV}}^{-1} \cdot \epsilon_{\text{p}}^{-1} \cdot \phi \cdot s^{-1} \cdot \text{keV}^{-1} \cdot \text{cm}^{-2} \cdot \text{str}^{-1}
\]

where \( \epsilon_{\text{keV}} = \epsilon/1 \text{ keV} \) and \( \epsilon_{\text{p}} = 41.13 \). We estimated the expected CXB signal in the HXD-PIN spectrum using the latest response matrix for spatially uniform emission, ae_hxd_pinflat_20060809.rsp. The contribution from the CXB flux is estimated to be \( \sim 5\% \) of the NXB, comparable to the current systematic uncertainty of the NXB model itself. We confidently detect hard X-rays from RX J1713.7−3946 up to \( \sim 40 \text{ keV} \); at higher energies background uncertainty dominates the source flux.

The PIN data from the two OFF-pointing observations were analyzed in the same way as those from the on-source pointing. After subtraction of NXB and CXB, we do not find any significant hard X-ray emission that exceeds the background uncertainty. If we fit an NXB-subtracted spectrum of the OFF pointings (OFF1 and 2 are added) with the CXB spectral form defined by Eq. (1) but varying its normalization, we find a normalization factor of \( 1.7 \pm 0.2 \) (where the uncertainty includes only statistical errors). This suggests the possible presence of diffuse emission from the Galactic plane (Valinia & Marshall 1998) at a level of about \( 70\% \) of the CXB. This is below the uncertainty in the NXB model and will not significantly affect the RX J1713.7−3946 spectrum. It should be noted that the RXTE PCA spectrum of RX J1713.7−3946 in the 2–30 keV range (Pannuti et al. 2003) is likely contaminated by the Galactic ridge emission because of its much...
larger FOV (\(\sim 1^\circ\) FWHM). Instead of the background model, we subtracted the OFF-pointing spectrum from the on-source spectrum as shown in Figure 4. We found that the two methods of background subtraction gave almost identical results within the statistical error, though the OFF-subtracted spectrum seems to be systematically lower than the model-subtracted spectrum. This could indicate the level of the systematic error in the background model or some contribution from the diffuse ridge component.

Before proceeding with the spectral fitting, we checked the detector response against an extended source like RX J1713.7−3946, since this is the first clear case that the Suzaku HXD gives a spectral measurement for any source larger than the PIN collimator. We performed Monte Carlo simulations with the code simHXD (Terada et al. 2005) to study the PIN response for an extended source. Hard X-rays from a \(2^\circ \times 2^\circ\) sky area centered on the optical axis were uniformly distributed over the entrance aperture of the HXD, and their interactions with the detector system were tracked. Figure 5 shows the simulated spectra of a diffuse source (red) and a point source at the XIS-nominal position (black). The comparison demonstrates that spatial extent does not affect the observed spectral shape, consistent with expectations that the built-in passive collimator (50 \(\mu\)m thick phosphor bronze sheets) should almost completely absorb hard X-rays below 80 keV and, consequently, that the angular response is not energy-dependent. In Figure 6 we show the angular response of the PIN detector determined by the passive collimator. The difference of the spectral shape is so small that it corresponds to the difference of photon index of 0.01 when fitted with a power-law model using the same response matrix. We conclude that the extended nature of the source does not cause any spectral steepening or flattening, at least for energies below 40 keV. In the following, we therefore fit the PIN spectrum simply using the point-source response matrix at the XIS-nominal position, \texttt{ae\_hxd\_pinxnom\_20060814.rsp}. 

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**Fig. 4.** Background-subtracted PIN spectra, using the background model (black) and off-source spectrum (red).

**Fig. 5.** Simulated PIN spectra for a point (red) and extended source (black). The bottom panel shows the ratio between them. This demonstrates that the energy-dependence of the PIN response for an extended source is same as that for a point source.

**Fig. 6.** Angular response of the PIN detector as defined by the built-in passive collimator. Contours indicate the effective area as a function of incoming photon direction. The angular response is independent of energy below 80 keV.
We fitted the background-subtracted PIN spectrum with a simple power law model: \( dN/dE \propto E^{-\Gamma} \). The best-fit parameters are summarized in Table 2. We present two cases, one using the NXB+CXB model as a background spectrum, and the other using the OFF-pointings as a background template. Both methods agree with each other. Hereafter we only use spectral results with the NXB+CXB model. The photon index obtained, \( \Gamma = 3.2 \pm 0.2 \), is much larger than that for previous soft X-ray (below 10 keV) results, \( \Gamma \approx 2.4 \) (Slane et al. 1999). Given the current reproducibility of the NXB model of \( \sim 5\% \), the systematic error due to uncertainties in the NXB modeling is found to be \( \Delta \Gamma \approx 0.2 \). A spectral cutoff around 10 keV seems necessary to account for the spectral transition from the flat X-ray spectrum with \( \Gamma = 2.4 \pm 0.05 \) (Slane et al. 1999) into the steep spectrum with \( \Gamma = 3.2 \pm 0.2 \) in the PIN domain. Below we further confirm this important finding based on spectroscopy with the XIS.

3.2. XIS data Analysis

Figure 7 shows the XIS images from our observation in the soft (1–5 keV) and hard (5–10 keV) bands. Both images were smoothed with a Gaussian kernel with \( \sigma = 0.3 \) and background-subtraction was carried out for each of them. We utilized the Night Earth Background Database consisting of event data accumulated while the satellite was viewing the night earth where the non X-ray background becomes dominant. After background subtraction, the vignetting effects of the X-ray mirrors were corrected by means of the simulation program xissim (Ishisaki et al. 2007). It should be noted that the two XIS images in the soft and hard bands are similar to each other. This indicates that spectral changes reported by Cassam-Chenaî et al. (2004) across the SW part are not dramatic in our data set.

The XIS provides higher quality spectra of the SNR RX J1713.7–3946 compared with previous missions thanks to its low background level, good energy resolution, excellent energy response below 1 keV, and large effective area (Koyama et al. 2007). We accumulated X-ray photons from the region shown in Fig. 7. Since RX J1713.7–3946 is situated near the Galactic plane, the background spectrum needs to be accumulated from a nearby, source-free region. We extracted the background spectra from the OFF observations. In the fitting procedure, the standard RMF files (response matrices of the XIS) version 2006-02-13 were used, whereas ARF files (response of the XRT) were produced with the xissimarfgen software version 2006-10-26 (Ishisaki et al. 2007). The energy range of 0.4–12 keV, to which the XIS FI chips are sensitive, is used in fitting, but a range of 1.7–1.9 keV is excluded from the spectra because of large systematic uncertainties in the response matrices in this band. Background uncertainty is most significant for the low energy (<0.6 keV) part of the spectrum where the signal to background ratio drops. We do not take account of this issue in detail, except to note that the spectral fits reported here are not affected by this. Finally, we co-added the three spectra, RMF files, and ARF files from the FI chips to produce a single data set for the XIS.

Following previous studies, we first fitted the XIS spectrum in the 0.4–12 keV band with a simple power law attenuated by interstellar absorption. We found a power law model fails to fit the data, giving a large reduced chi-squared of \( \chi^2_{\text{red}} = 1.81 \) for 302 degrees of freedom. Though statistically unacceptable, the derived photon index of \( \Gamma = 2.39 \pm 0.01 \) and absorbing column density of \( N_H = (0.87 \pm 0.01) \times 10^{22} \text{ cm}^{-2} \) are in good agreement with the ASCA result in this region: \( \Gamma = 2.40 \pm 0.05 \) and \( N_H = (0.79 \pm 0.50) \times 10^{22} \text{ cm}^{-2} \) (Slane et al. 1999). In Figure 8 (left panels) we show the XIS spectrum with the best-fit power-law function and residuals (data minus model). There remains a correlated pattern to the residuals in the power-law fit. This failure of the power-law fit argues that a more complicated spectral model is required. Furthermore, the difference in fitted photon indices between the XIS and HXD PIN data says that the model needs to roll-off or steepen with energy across the broad bandpass.

We therefore fit the XIS spectrum with three other models: a power-law with two types of an exponential cutoff (cutoff power law), (1) \( \epsilon^{-\Gamma} \exp \left[ -\epsilon/\epsilon_c \right] \) and (2) \( \epsilon^{-\Gamma} \exp \left[ -\sqrt{\epsilon/\epsilon_c} \right] \), and (3) a broken power law. Unlike the pure power-law case, these mathematical functions give acceptable fits (see Table 3). Figure 8 (right panels) shows the XIS spectrum with the best-fit \( \epsilon^{-\Gamma} \exp \left[ -\epsilon/\epsilon_c \right] \) function together with its residuals. The wavy residuals seen in the power-law fit clearly disappear by introducing the cutoff. The cutoff power-law fit gives a power law \( \Gamma = 1.96 \pm 0.05 \) with a cutoff at \( \epsilon_c = 8.9^{+1.1}_{-0.9} \text{ keV} \), where the fit function has a form \( \epsilon^{-\Gamma} \exp \left[ -\epsilon/\epsilon_c \right] \). Also, we find a hard power law \( \Gamma = 1.50 \pm 0.09 \) with a lower cutoff at \( \epsilon_c = 1.2^{+0.3}_{-0.2} \text{ keV} \) with the fit function of \( \epsilon^{-\Gamma} \exp \left[ -\sqrt{\epsilon/\epsilon_c} \right] \). The broken power-law model also reduces the correlated pattern in the residuals. The best-fit function is composed of two distinct power laws of \( \Gamma_1 = 2.18 \pm 0.03 \) and \( \Gamma_2 = 2.53 \pm 0.02 \) with a break energy of \( \epsilon_b = 3.13 \pm 0.15 \text{ keV} \).

We also performed spectral fits with the so-called SRCUT model (Reynolds 1998) in the XSPEC package, which describes the synchrotron spectrum from electrons following an exponentially-cutoff power law distribution in energy. In XSPEC, its spectral shapes for different parameters are tabulated based on numerical calculations convoluting a well-known synchrotron formula for a single electron with the energy distribution of electrons of the form \( E^{-s} \exp (-E/E_0) \). The synchrotron spectrum has a power-law form at radio frequencies (with photon index \( \Gamma = \alpha + 1 \), where \( \alpha \) is nominally the spectral index in the radio band), with a rolloff energy \( \epsilon_{\text{roll}} \) (nominally the energy where the exponential cut-off reduces the flux by a factor of 4 below the extrapolation of the radio power-law spectrum). We fixed the index to a typical value for SNRs of \( \alpha = 0.5 \). A good fit was obtained with a best-fit rolloff energy of \( \epsilon_{\text{roll}} = 0.95 \pm 0.04 \text{ keV} \). The roll-off energy obtained in this way is similar to the cutoff energy \( \epsilon_c = 1.2 \text{ keV} \) ob-
Table 2. Power-law fitting to the HXD PIN spectrum

| Pointing           | Background                  | $\Gamma$   | Flux $^\dagger$ (10–40 keV) | $\chi^2_\nu$ |
|--------------------|-----------------------------|------------|-----------------------------|--------------|
| RX J1713.7−3946 SW | model (NXB+CXB)             | $3.2 \pm 0.2$ | $2.5 \pm 0.1$            | 1.15 (36)    |
| RX J1713.7−3946 SW | OFF1+2                     | $3.2 \pm 0.3$ | $2.3 \pm 0.2$            | 0.92 (27)    |

Notes: 
* Errors represent 90% confidence. 
† In units of mCrab.

Fig. 7. The XIS images of RX J1713.7−3946 in (a) the soft 1–5 keV and (b) the hard 5–10 keV bands. Three FI chips are combined. North is up and east is to the left. The images have dimension $17' \times 17'$. The color scale indicates the surface brightness in a linear scale. The green box shown in (a) is the region from which we extracted the XIS spectrum.

3.3. Suzaku Wide Band Spectrum

We now combine the HXD PIN spectrum with the XIS spectrum to fully exploit the broadband capability of Suzaku. Since the source is extended and the HXD PIN observes a much wider field than the XIS, the relative normalization factor derived for a point source, $\kappa = 1.13 \pm 0.01$ (Ishida et al. 2006), is not applicable in our case. We note that the relative normalization factor $\kappa$ is defined here as the flux density at 12 keV determined by the PIN relative to that determined by the XIS. Therefore, it is necessary to calculate the proper scaling factor between the XIS and the HXD for a diffuse emission source. We determined the normalization factor $\kappa$, which takes into account the larger FOV of the PIN, by convolving the emission distribution of the ASCA image with the angular response of the HXD-PIN defined by the passive collimator. It is assumed that the spatial distribution of X-ray surface brightness is independent of energy in the ASCA-Suzaku band over the entire remnant. We determined the normalization factor to be $\kappa = 6.6$ using the ASCA 5–10 keV image, with a possible systematic error of $\sim 10$–20%. (The value of $\kappa$ does not depend sensitively on the choice of ASCA bandpass. If instead we use the ASCA 1–5 keV image a slightly different value, $\kappa = 6.5$, is obtained.)

In Figure 9, we show the XIS+PIN spectra together with the power law, cutoff power law, broken power law, and SRCUT models. The model parameters are the best-fit values determined by fitting the XIS spectrum alone (see Table 3), and the best-fit models are extrapolated to the PIN bandpass after multiplication by the factor $\kappa = 6.6$. The power-law model clearly conflicts with the PIN data as does the broken power law model, which was a good description of the XIS data alone. Although the shape of the SRCUT model in the PIN band (which can be characterized as a power law with a photon index of $\Gamma \simeq 3.3$) is a good match to the data, the level of hard X-rays this model produces is about 40% too high, somewhat more than the estimated systematic error in the normalization factor $\kappa$ of $\sim 20\%$. If we change the exponent, $\alpha$, of the SRCUT model by $\pm 0.1$, this result still holds. Although the cutoff power-law function of $e^{-\Gamma} \exp\left[\frac{-\sqrt{\epsilon/\epsilon_c}}{\epsilon/\epsilon_{real}}\right]$ satisfactorily reproduces the level of the observed PIN flux, the model flux in this case (ap-
proximately a power law with $\Gamma \simeq 3.7$ in the PIN band) falls more steeply than the data. A slower exponential form of $e^{-\Gamma} \exp[-(\epsilon/\epsilon_c)]$, which gives $\Gamma \simeq 3.5$ in the PIN band for its best-fit model, seems to yield the best match to the PIN data both in the absolute flux and spectral shape. We conclude that the evidence for a curvature in the broad band Suzaku spectrum of RX J1713.7–3946 is secure. However, it is premature at this time to argue that, for example, the cutoff power-law models are a better description of the emission conditions in the SNR than the SRCUT model based on the XIS+PIN joint spectral analysis, simply because the two data sets do not come from the same spatial regions. Modest spatial variations in the emitting conditions could produce flux or spectral differences similar to those seen in the PIN band for the cutoff power-law and SRCUT models. Furthermore, even spatial/spectral variations in the synchrotron emission within the joint XIS+PIN field of view (as seen by Cassam-Chenaï et al. (2004)) could account for the modest differences in the cutoff power-law and SRCUT models in the PIN band.

### 3.4. Upper Limits on Thermal Emission

One of the most remarkable characteristics of RX J1713.7–3946 is the complete lack of a thermal X-ray emission component as expected from the hot shocked gas in the SNR. Our XIS spectrum, similar to previous studies (Slane et al. 1999; Cassam-Chenaï et al. 2004), shows no signs of thermal emission. In the following we set an upper limit on the density of shocked hot gas from the upper limit on the thermal emission measure.

To derive the allowable level of thermal emission underneath the synchrotron spectrum, we added a thermal component to the cutoff power-law model obtained by fitting the XIS spectrum (see Table 3 for the parameters). We used the APEC model for the thermal emission model and assumed solar composition. Then, we determined $3\sigma$ upper limits on the emission measure, $EM = \int n_e n_H dV/4\pi D^2$, as a function of electron temperature $kT_e$ over the range 0.05 keV to 1 keV. Above 1 keV, the upper limit has only a weak dependence of temperature (Slane et al. 1999). Here, $n_e$, $n_H$, $V$, and $D$ are the number density of electrons and hydrogen, the volume of the hot gas, and the distance to the remnant, respectively.

Figure 10 shows the $3\sigma$ upper limits as a function of temperature. The upper limits grow quite large for $kT_e \lesssim 0.2$ keV. The emission measure can be as large as $10^{14}$ cm$^{-5}$ if we assume a temperature as low as $\sim 0.05$ keV. From the emission measure, we can estimate the number density of shocked gas. By assuming $n_e = 1.2 n_H$, uniform distribution of gas inside the remnant, and that the spectral region covers 8% of the whole volume of the remnant (a sphere of 30′ radius), we relate the gas density ($n = n_H$) to the emission measure as

| Function               | $N_H$ (10$^{22}$ cm$^{-2}$) | $\Gamma$ | $\epsilon_c/\epsilon_b/\epsilon_{roll}$ (keV) | $F_{1-10}$ (10$^{-15}$ erg s$^{-1}$ cm$^{-2}$) | $\chi^2_{\nu}$ (ν) |
|-----------------------|-----------------------------|----------|-----------------------------------------------|-----------------------------------------------|-------------------|
| power law ($e^{-\Gamma}$) | 0.87 ± 0.01                | 2.39 ± 0.01 | —                                             | 6.07 ± 0.09                                   | 1.81 (302)        |
| $e^{-\Gamma} \exp[-(\epsilon/\epsilon_c)]$ | 0.77 ± 0.01                | 1.96 ± 0.05 | 8.9$^{+1.1}_{-0.9}$                           | 5.67$^{+0.10}_{-0.05}$                         | 1.03 (301)        |
| $e^{-\Gamma} \sqrt{\epsilon/\epsilon_c}$ | 0.74 ± 0.02                | 1.50 ± 0.09 | 1.2$^{+0.3}_{-0.2}$                           | 5.61 ± 0.40                                   | 1.00 (301)        |
| broken power law       | 0.79 ± 0.01                | 2.18 ± 0.03/2.53 ± 0.02 | 3.13 ± 0.15                                   | 5.75 ± 0.17                                   | 1.00 (300)        |
| srcut                  | 0.77 ± 0.01                | 1.5 fixed  | 0.95 ± 0.04                                   | 5.71 ± 0.02                                   | 1.05 (302)        |

Notes.

* Errors quoted at 90% confidence.
† Corrected for absorption.

Fig. 8. (Left) The XIS spectrum in the 0.4–12 keV band together with the best-fit power-law model. The lower panel shows the residuals between the data and model. (Right) Same as the left panel but with the best-fit cutoff power-law model.

Table 3. Model fitting to the XIS spectrum (0.4–12 keV)*
Fig. 9. XIS+PIN spectra in the energy range 0.4–40 keV are shown with the best-fit models obtained by fitting the XIS spectrum alone: (a) power law, (b) $e^{-T \exp \left[-\left(\epsilon/e_c\right)\right]}$, (c) $e^{-T \exp \left[-\sqrt{\epsilon/e_c}\right]}$, (d) broken power-law, and (e) SRCUT. The lower panels show the ratio between the data points and the model values.
the power law with $\exp(-\epsilon)$-type cutoff model, while the lower bound is derived with $\exp(-\sqrt{\epsilon})$-type cutoff. Given this fact, we need to be careful in discussing the physical meanings of the position of the spectral cutoff. We briefly explore the implications of the Suzaku broadband spectrum in a separate paper (Uchiyama et al. 2007). More detailed discussions on this issue will be given elsewhere (T. Tanaka et al. in preparation).

If the magnetic field exceeds $10 \, \mu G$ in the shell (e.g., see Berezhko, & Völk (2006)), the TeV $\gamma$-rays detected from the remnant should be explained by protons producing $\pi^0$-decay $\gamma$-rays, rather than by electrons emitting $\gamma$-rays via inverse Compton scattering (Aharonian et al. 2006). The hadronic model requires the total energy content of protons to amount to

$$W_p \approx 10^{50} \left( \frac{D}{1 \, \text{kpc}} \right)^2 \left( \frac{n}{1 \, \text{cm}^{-3}} \right)^{-1} \text{erg},$$

in order to explain the observed TeV $\gamma$-ray flux (Aharonian et al. 2006). Therefore, a matter density of $\sim 0.2 \, \text{cm}^{-3}$ is needed, assuming the typical kinetic energy released by a supernova of $10^{51}$ erg and a conversion efficiency to high energy protons of 50%. To reconcile this density value with the upper limit on thermal X-ray emission (§3.4), the electron temperature must be of order $0.1 \, \text{keV}$ (or lower), otherwise thermal emission ($\propto n^2$) would have been detected with the Suzaku XIS. The low-temperature of thermal electrons may indicate that efficient particle acceleration drains the energy of the shock, thus suppressing gas heating at the shock (Ellison et al. 2001).

Strong (high Mach number) shocks in young shell-type SNRs do accelerate high-energy particles with remarkably high efficiency, thus providing an ideal laboratory to study high-energy particle acceleration in the Universe. Suzaku has excellent capability for determining the spectral form of X-ray synchrotron emission thanks to its broadband spectral coverage from 0.4 to 40 keV. The observed cutoff energy in the synchrotron X-ray spectrum suggests that shock acceleration proceeds at nearly the maximum possible rate. Combined with the broad TeV $\gamma$-ray spectrum (in the 0.3--100 TeV band) measured recently with HESS, our Suzaku observations of RX J1713.7--3946 provide stringent constraints on shock-acceleration of the highest energy particles in our Galaxy.

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