STUDY OF NONTHERMAL EMISSION FROM SNR RX J1713.7−3946 WITH SUZAKU

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ABSTRACT

We present results obtained from a series of observations of the supernova remnant RX J1713.7−3946 by Suzaku. Hard X-rays have been detected up to ~40 keV. The hard X-ray spectra are described by a power law with photon indices of ~3.0, which is larger than those below 10 keV. The combination of the spatially integrated XIS and HXD spectra clearly reveals a spectral cutoff which is linked to the maximum energy of accelerated electrons. The broadband coverage of Suzaku allows us to derive, for the first time, the energy spectrum of parent electrons in the cutoff region. The cutoff energy in the X-ray spectrum indicates that the electron acceleration in the remnant proceeds close to the Bohm diffusion limit. We discuss the implications of the spectral and morphological properties of the Suzaku data in the context of the origin of nonthermal emission. The Suzaku X-ray and H.E.S.S. gamma-ray data together hardly can be explained within a pure leptonic scenario. Moreover, the leptonic models require a weak magnetic field, which is inconsistent with the recently discovered X-ray filamentary structures and their short-term variability. The hadronic models with strong magnetic fields provide reasonable fits to the observed spectra, but require special arrangements of parameters to explain the lack of thermal X-ray emission. For morphology studies, we compare the X-ray and TeV gamma-ray surface brightness. We confirm the previously reported strong correlation between X-rays and TeV gamma rays. At the same time, the Suzaku data reveal a deviation from the general tendency, namely, the X-ray emission in the western rims appears brighter than expected from the average X-ray to gamma-ray ratio.

Subject headings: acceleration of particles — ISM: individual (RX J1713.7−3946) — supernova remnants — X-rays: ISM

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1. INTRODUCTION

Supernova remnants (SNRs) have long been considered to be likely acceleration sites of cosmic-ray particles below the energy of the knee, ~10^{15} eV. The energy supply needed to explain the energy density of cosmic rays is satisfied if ~1%–10% of the energy of each supernova is transferred to accelerated particles. In addition, the well-developed theory of diffusive shock acceleration nicely explains the universal power-law spectrum of cosmic rays (e.g., Blandford & Eichler 1987; Malkov & Drury 2001). Although synchrotron emission detected in the radio band supports this idea observationally, no evidence of acceleration to TeV energy had been observed until recently. During the last decade, such evidence has been found through observations of X-rays and TeV gamma rays from several shell-type SNRs. Koyama et al. (1995) discovered synchrotron X-rays from the shell of SN 1006, which indicates that electrons are accelerated up to multi-TeV energies. This finding was followed by detections of synchrotron X-rays from other SNRs, including RX J1713.7−3946 (e.g., Koyama et al. 1997; Slane et al. 2001). Further evidence for multi-TeV particles (electrons and/or protons) has been provided by the discovery of TeV gamma rays from some SNRs, such as Cassiopeia A (Aharonian et al. 2001) or RX J1713.7−3946 (Muraiishi et al. 2000), although their spectral parameters and morphologies were not well determined due to the limited sensitivity of TeV observatories. Subsequently, high-quality morphological and spectral studies have been performed by H.E.S.S. (e.g., Aharonian et al. 2004, 2006, 2007). These pioneering measurements by the H.E.S.S. telescope, together with the high-resolution X-ray data, have enabled direct comparison of X-ray and TeV gamma-ray data.

The shell-type SNR RX J1713.7−3946 (also known as G347.3−0.5), is one of the best-studied SNRs from which both nonthermal X-rays and TeV gamma rays are detected. This SNR was discovered in soft X-rays during the ROSAT All-Sky Survey (Pfeffermann & Aschenbach 1996). The ASCA satellite, with wider energy coverage than that of ROSAT, revealed that the X-ray spectrum is featureless and can be best interpreted as synchrotron emission from very high energy electrons in the TeV regime (Koyama et al. 1997; Slane et al. 1999). The X-ray spectrum was well fitted with a power-law function of photon index \( \Gamma = 2.2\pm0.4 \) and interstellar absorption column density \( N_{\text{H}} = 0.6\pm0.8 \times 10^{22} \text{cm}^{-2} \), without any observable evidence for a thermal emission component. Subsequent observations by Chandra and XMM-Newton have unveiled structure with a complex network of bright filaments and knots, in the western part of the SNR (Uchiyama et al. 2003; Lazendic et al. 2004; Cassam-Chenaï et al. 2004; Hiraga et al. 2005).
TeV gamma-ray emission from RX J1713.7−3946 was first reported by the CANGAROO collaboration in 1998 (Muraishi et al. 2000), and confirmed by the subsequent observations with CANGAROO-II in 2000 and 2001 (Enomoto et al. 2002). Later, the H.E.S.S. collaboration obtained a resolved image of the source in TeV gamma rays (Aharonian et al. 2004), showing that the gamma-ray emission from RX J1713.7−3946 arises mainly in the shell. These observations revealed a striking correlation between the X-ray and the gamma-ray images, which indicates a strong connection between the physical processes responsible for X-ray and TeV gamma-ray emission components (Aharonian et al. 2006). Based on the spectral and morphological information, they discussed two possible gamma-ray emission scenarios, one in which gamma rays are generated by inverse Compton scattering of electron–positron pairs, and another in which the decay of secondary $\pi^0$-mesons is responsible for gamma rays (hadronic scenario). Later observations with H.E.S.S. revealed that the flux extends to 30 TeV, and likely beyond, which implies particle acceleration up to energies well above 100 TeV for either model (Aharonian et al. 2007).

Most recently, our X-ray observations using Chandra and Suzaku have provided important clues for understanding the acceleration process in the SNR. From a series of observations of the northwest part of the SNR with Chandra in 2000, 2005, and 2006, we discovered that compact regions of the northwest (NW) shell are variable in flux on a 1 yr timescale (Uchiyama et al. 2007). The fast variability was interpreted as 1 yr scale acceleration and synchrotron cooling of electrons with amplified magnetic fields of the order of 1 mG. Such a large magnetic field in compact regions strongly favors $\pi^0$-decay emission as the origin of TeV gamma rays. In addition, thanks to the wide-band coverage of Suzaku and its low background level, we were able to measure a hard X-ray spectrum up to 40 keV from the southwest portion of RX J1713.7−3946, with a clear indication of a high-energy cutoff in the synchrotron spectrum (Takahashi et al. 2008, hereafter Paper I). Combined with the upper limit on a shock speed of 4500 km s$^{-1}$ placed by Chandra, the cutoff energy determined by the Suzaku observation of the southwest part indicates that particle acceleration within the SNR shock is so efficient that it approaches the theoretical limit corresponding to the so-called Bohm diffusion regime (e.g., Malkov & Drury 2001).

In this paper, we present results of mapping observations of RX J1713.7−3946 with Suzaku, which covers about two-thirds of the SNR region with 11 pointings. The low background level of the Hard X-ray Detector (HXD) enables us to detect hard X-ray emission up to ~40 keV from each of the pointings. At the same time, its small field of view (FoV) of ~25$^\circ \times 25^\circ$ FWHM gives us information about the spatial distribution of hard X-ray emission and spectral differences from region to region. Thanks to its low instrumental background and large effective area, the other detector system aboard Suzaku, the X-ray Imaging Spectrometer (XIS), also uncovers new observational facts, such as spectral features below 10 keV and the morphology of relatively dim regions left unclear in previous studies by ASCA, Chandra, and XMM-Newton. By combining the XIS and HXD spectra summed over the data from all the pointings, we show a wide-band X-ray spectrum (0.4–40 keV) with quite high statistics, with which we investigate not only the existence of a cutoff, but also its shape. We then compare the cutoff shape obtained with theoretical predictions.

In § 2, we describe our Suzaku observations and the data-reduction procedures. Analysis and results of HXD and XIS data are shown in § 3.1 and § 3.2, respectively. We present the wide-band spectrum by connecting the XIS and the HXD data in § 3.3. A detailed study regarding the cutoff structure is also given there. Section 4 is devoted to multiwavelength spectral and morphological studies. The results obtained are discussed in the following section, and the results are finally summarized. Throughout this paper, we assume that the distance to RX J1713.7−3946 is close to 1 kpc, as proposed by Koyama et al. (1997) based on the $N_H$ value. A similar distance has been claimed based on the NANTEN CO data (Fukui et al. 2003; Moriguchi et al. 2005). The typical age of the remnant for such a distance is estimated to be of order of 1000 yr, which can be an indication of association of RX J1713.7−3946 with an explosion in a.d. 393, as proposed by Wang et al. (1997).

2. SUZAKU OBSERVATIONS AND DATA REDUCTION

The Suzaku observatory (Mitsuda et al. 2007) is the fifth Japanese X-ray astronomy satellite, jointly developed by Japan and the US. Its scientific payload consists of two co-aligned detector systems, the XIS (Koyama et al. 2007) and the HXD (Takahashi et al. 2007; Kokubun et al. 2007). The XIS consists of four X-ray CCD cameras, which are located in the foci of X-ray telescopes (XRT; Serlemitsos et al. 2007). Three of the XIS sensors are front-illuminated (FI; 0.4–12 keV) CCDs, and the other is back-illuminated (BI; 0.2–12 keV). The non-imaging, collimated hard X-ray instrument, the HXD, covers the 10–600 keV bandpass. Two main detector units, silicon PIN diodes and GSO scintillators, are buried at the bottom of well-type active shield of BGO. The former covers the lower energy band of 10–60 keV, while the latter detects higher energy photons of 40–600 keV.

We performed 11 pointing observations of RX J1713.7−3946 with Suzaku. The observation log is summarized in Table 1, and the pointing position of each observation is shown in Figure 1. The southwest part of the SNR, labeled as pointing 0, was observed in 2005 during the Performance Verification phase, while the other 10 observations were performed in 2006 during the Suzaku AO1 phase. Since the SNR is located on the Galactic plane, it is of importance to check the hard X-ray background associated with the Milky Way. We therefore observed two nearby background regions containing no bright X-ray point sources. The pointing positions of these "OFF" observations are shown with red squares in Figure 1. The XIS was operated in the normal full-frame clocking mode without spaced-row charge injection during

| Pointing ID | ObsID | Coordinates (J2000) | Exposure XIS/HXD (ks) | Date |
|-------------|-------|---------------------|-----------------------|------|
| 0.............| 100026010 | 17 12 17.0, −39 56 11 | 55/48 2005 Sep 26 |
| 1.............| 501063010 | 17 11 51.5, −39 31 13 | 17/17 2006 Sep 11 |
| 2.............| 501064010 | 17 12 38.0, −39 40 14 | 18/22 2006 Sep 11 |
| 3.............| 501065010 | 17 12 38.2, −39 22 15 | 19/18 2006 Sep 11 |
| 4.............| 501066010 | 17 11 04.5, −39 40 10 | 19/21 2006 Sep 12 |
| 5.............| 501067010 | 17 11 03.1, −39 22 16 | 19/16 2006 Sep 12 |
| 6.............| 501068010 | 17 14 11.6, −39 40 14 | 20/19 2006 Sep 13 |
| 7.............| 501069010 | 17 14 11.4, −39 22 15 | 12/11 2006 Sep 19 |
| 8.............| 501070010 | 17 14 11.8, −39 58 14 | 20/19 2006 Sep 19 |
| 9.............| 501071010 | 17 12 17.6, −39 18 50 | 16/15 2006 Sep 20 |
| 10............| 501072010 | 17 15 44.5, −39 40 10 | 15/15 2006 Oct 5 |
| OFF1...........| 100026020 | 17 09 31.9, −38 49 24 | 28/24 2005 Sep 25 |
| OFF2...........| 100026030 | 17 09 05.1, −41 02 07 | 30/28 2005 Sep 28 |

Note:—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
all the observations. Since the results from pointing 0, together with those from the OFF observations, have already been reported in Paper I, we do not give a detailed description of the analysis and results for these data here.

We used data products from the pipeline processing version 1.2. For the XIS analysis, we retrieved “cleaned event files,” which are screened using standard event selection criteria. For the 2006 data, we recalculated the values of pulse invariant (PI) and the grade values, since incorrect CALDB was applied to the pipeline processing of these data, as announced by the Suzaku instrument teams. We further screened the cleaned events with following criteria as recommended by the Suzaku instrument teams: (1) cutoff rigidity larger than 6 GV and (2) elevation angle from the Earth rim larger than 10°. For the HXD data, uncleaned event files were screened using standard event-screening criteria. The exposure times after these screenings are shown in Table 1. Due to unstable operation of 16 PIN diodes installed in Well-counter units W00–W03 (hereafter W0), the bias voltage for these diodes was reduced to 400 V from the nominal voltage of 500 V on 2006 May 26. On 2006 October 4, the bias voltage of 16 more PIN diodes (the PIN diodes in the Well-counter units of W10–W13; hereafter W1) was reduced to 400 V for the same reason. The reduction of the PIN diode bias voltage leads to a decrease of their effective area, and also affects their energy response. Since the current response matrices do not include these effects, only the PIN diodes with a bias voltage of 500 V are utilized in the following analysis. Throughout this paper, the data reduction and analysis are performed using HEADAS 6.2, and the spectral fitting is done with XSPEC 11.3.2.

3. ANALYSIS AND RESULTS

3.1. HXD Data Analysis

3.1.1. Spectral Analysis

The HXD PIN spectrum from each pointing was constructed and compared with the background model estimated for the each observation period. In the analysis below, the non-X-ray background (NXB) model (Watanabe et al. 2007) provided by the
The systematic errors due to the misestimation of NXB were examined in another way. Considering the physical size of this target, the emission from the remnant should be constant during the observations. Therefore, background-subtracted light curves should be constant during an observation. Although the light curves shown are almost constant within statistical errors, the background-subtracted count rate increases higher when the total count rate increases for pointings 0 and 8. The light curves for pointings 0 and 8 are shown in Paper I and Figure 3, respectively. Since this behavior is thought to be caused by misestimation of the NXB, we examined how much the photon indices change with and without those time regions. When we discard the time region corresponding to the last bin of Figure 3, the photon index changes by \( \Delta \Gamma \lesssim 0.2 \) from the values in Table 2.

Diffuse emission from the Galactic plane can also affect the spectra. However, no emission above the 5% level of the NXB was detected from the OFF pointings (Paper I). Moreover, when the excess counts marginally detected from the OFF pointings are added to the background spectrum for each pointing, the fitting result agrees within the statistical errors.

### 3.1.2. Spatial Distribution of Hard X-Ray Emission

Using the spectral parameters obtained for the 11 pointings, we attempt to reconstruct the spatial distribution of the hard X-ray

\[
\frac{dN}{d\varepsilon} = 7.9 e^{-1.29} \exp \left( -\frac{\varepsilon_{\text{keV}}}{\varepsilon_{\text{p}}} \right) \text{photons s}^{-1} \text{keV}^{-1} \text{cm}^{-2} \text{sr}^{-1},
\]

where \( \varepsilon_{\text{keV}} = \varepsilon/1 \text{keV} \) and \( \varepsilon_{\text{p}} = 41.13 \). We estimated the CXB signal in each HXD PIN spectrum using the response matrix for spatially uniform emission, `ae_hxd_pinflat123_20060809.rsp`, `ae_hxd_pinflat123_20060809.rsp`, and `ae_hxd_pinflat23_20060809.rsp`. The contribution from the CXB flux to the detected count rate is estimated to be \( \sim 5\% \) of the NXB.

Figure 3 shows the HXD PIN spectrum obtained from pointing 8, where a clear detection of hard X-rays can be seen. Likewise, the HXD PIN detected signals from all other pointings with a count rate of 20%–50% of the NXB. We fitted the background-subtracted spectra with a simple power-law model: \( \frac{dN}{d\varepsilon} \propto \varepsilon^{-\Gamma} \). Since the extended nature of the source does not cause any spectral steepening or flattening (Paper I), we used the point-source response matrix at the XIS-nominal position, `ae_hxd_pinxinom123_20060814.rsp`, `ae_hxd_pinxinom123_20060814.rsp`, and `ae_hxd_pinxinom23_20060814.rsp`. Table 2 gives the best-fit parameters with the statistical errors at 90% confidence level. The photon indices obtained are generally larger than those obtained from the corresponding XIS spectra (see below). This difference indicates that a spectral cutoff is not unique to the SW region (Paper I), but a common feature throughout the remnant.

In order to confirm the results obtained above, we evaluated the systematic errors due to uncertainties in the NXB modeling. As described in Mizuno et al. (2006), the current reproducibility of the NXB model is \( \sim 5\% \). Therefore, we examined how much the values of the photon index change by increasing or decreasing the background model by 5%. The systematic errors were found to be smaller than the statistical errors indicated in Table 2.
emission. Since we expect spatial variation of both brightness and spectral index, we use a Monte Carlo simulator, simHXD (Terada et al. 2005), for the estimation. We input the spatial distribution of brightness and spectral index into simHXD, and compare the simulated spectra with observed ones shown in § 3.1.1.

First, we simulated by taking a simple model in which the brightness distribution is same as the ASCA image shown in Figure 4, and the spectral index is constant at $\Gamma = 3.0$ throughout the SNR (simulation1). By using the ASCA image as an input to simHXD, we simulated hard X-ray spectra in 10–40 keV that are expected to be observed by the PIN in each pointing. Figure 5 compares the flux from the observations and the simulations. In this figure, each value is normalized to that of pointing 0. Here, the systematic error for each observational data point is $\sim 20\%$ if we use the 5% of the background as systematic errors. The observations and the simulations appear consistent with each other. Therefore, we expect that the brightness distribution above 10 keV is not drastically different from the distribution below 10 keV.

The largest discrepancy between the observation and the simulation is found for pointing 4. In this pointing, there is a known point source at the corner of the HXD-PIN field of view. The source is listed in the second IBIS/ISGRI Soft Gamma-Ray Survey Catalog (Bird et al. 2006) as IGR J17088–4008. According to Bird et al. (2006), the average flux of this source is $1.1 \pm 0.2$ mcrab in 20–40 keV and $2.2 \pm 0.3$ mcrab in 40–100 keV. It is noted that the source is not bright enough for IBIS/ISGRI to determine spectral parameters. The transmission of fine collimators of the HXD for the source is estimated to be $\sim 0.05$. The estimated count rate of this source corresponds to $\sim 2\%$ of the detected signals from pointing 4. However, the variability of this source could increase the count rate to a nonnegligible level. The observation and the simulation become consistent if the point source is 10 times brighter than its average value during the Suzaku observation. In addition, the angular response of the HXD near the edge of the FoV can have some uncertainties, since calibrations for a source with such a large offset angle is difficult. The uncertainties can affect our estimate of the contamination from IGR J17088–4008. At present, we cannot conclude whether the large difference between the observation and the simulation is due to the spatial distribution of the SNR emission or the point source in the FoV.

Next we tried another simulation, taking into account the spatial distribution of spectral indices (simulation2). We adopt a “toy model” shown in Figure 4, since the results of the spectral analysis presented in Table 2 suggest that the hard X-ray spectrum may be flatter in the inner region of the SNR than near the rim. In this model, the photon index of the inner region is set to $\Gamma = 2.6$ and that of the rim region is set to $\Gamma = 3.5$. The ASCA image was used to provide the brightness distribution at 10 keV.

Comparisons of the data and the simulation results are shown in Figures 5 and 6 for the flux and photon index, respectively. The detected flux obtained from simulation2 is somewhat similar to that from simulation1, and the simulation data generally follow the observational data. As for the distribution of photon indices, the toy model gives a similar distribution to the observational results for the western portion of the SNR. Obtaining a
better fit for the eastern region (pointings 7, 8, and 10) may require more complex assumptions than the toy model for simulation 2.

3.2. XIS Data Analysis

3.2.1. Image Analysis

Figure 7 shows mosaic images of RX J1713.7–3946, constructed using the data from XIS0, 2, and 3 (FI-CCDs). The upper panel shows the soft band image in 1–5 keV, and the lower panel shows the hard band image in 5–10 keV. Both images are smoothed with a Gaussian of \( \sigma = 0.3' \). Instrumental background signals are subtracted from both images. The signal to background ratio in the hard band is smaller than that in the soft band by 1 order of magnitude. Thus, the background must be carefully subtracted. We utilized the Night Earth Background Database, consisting of event data obtained when the satellite is looking at the night earth and the non-X-ray background becomes dominant. After subtracting the background, the vignetting effects of the XRTs were corrected by means of the simulation program called xissim (Ishisaki et al. 2007). In this program, an image from a flat field can be simulated by a Monte Carlo method.

As seen in Figure 7, the Suzaku XIS has covered most of the remnant. Thanks to little stray-light contamination of the XRTs and low background level of the XIS, high-quality images are obtained even in the high-energy band above 5 keV. The double shell structure revealed by XMM-Newton is clearly seen in the XIS images. In addition to the bright structures of the western part, the XIS revealed detailed morphology of the dim parts of the remnant. The dim structures are highlighted in Figure 8, which is the same as Figure 7a, but displayed with a different color scale. In this figure, the contours of the H.E.S.S. gamma-ray image (from Aharonian et al. 2007) are overlaid for comparison. As can be clearly seen, not only the bright rims but also the eastern portion shows a striking similarity between the two energy regimes. This correlation is discussed more quantitatively in § 3.4.

Two point sources seen in the soft band image are listed in the ROSAT bright source catalog. One is 1WGA J1714.4–3945, which was associated with a Wolf-Rayet star by Pfenniger & Aschenbach (1996). The other is 1WGA J1713.4–3949, which is located between the two FoVs of pointings 2 and 6. Lazendic et al. (2003) has suggested that this source may be the neutron star associated with the SNR.

Comparing the soft-band and hard-band images provides information about the spatial variations of the spectral properties. At first sight, the bright structures are very similar in the soft band and hard band images. In order to compare the images in more detail, a radial profile around the center of the SNR (\( \alpha_{2000} = 17^\circ13^\prime33.6^\prime, \delta_{2000} = -39^\circ45'36'' \)) is presented in Figure 9, where circular regions of 2.1' radius centered on the two point sources are excluded. The hard band to soft band ratio is significantly different between the bright outer region part and the interior. This difference suggests a corresponding difference in spectral properties.
1.7 and 1.9 keV, because there exist large systematic uncertainties whereas ARF files were produced using magenta polygons in Figure 7. In the spectral fitting discussed a background spectrum from the regions indicated with the function gives acceptable fits for all regions, and consistently a similar pattern is also seen in the data for region 6. Although not so drastic as region 1, which is shown in Paper I, a region 2 with the best-fit power law and the residuals in Figure 10. Nevertheless, the fits to the spectra of region 1, 2, and 6 are not acceptable even at the 99% confidence level. We show the spectrum of region 2. These results, together with the steeper than 0.4 keV or larger than 12 keV. We also excluded bins between 2005 and 2006. For regions 1–10 we therefore accumulated a background spectrum from the regions indicated with the magenta polygons in Figure 7. In the spectral fitting discussed below, the standard RMF files version 2006-02-13 were used, whereas ARF files were produced using xissimarfgen. Each spectrum is binned so that each bin contains at least 300 counts. After the binning, we ignore those bins whose energy is smaller than 0.4 keV or larger than 12 keV. We also excluded bins between 1.7 and 1.9 keV, because there exist large systematic uncertainties in the response matrices. Finally, we co-added the spectra, RMF files, and ARF files from the FI chips to produce a single data set for the XIS.

First, we fitted all the spectra with a simple power law absorbed by the interstellar medium. The results are summarized in Table 3. This model yields acceptable fits for most of the spectra. However, the fits to the spectra of region 1, 2, and 6 are not acceptable even at the 99% confidence level. We show the spectrum of region 2 with the best-fit power law and the residuals in Figure 10. Although not so drastic as region 1, which is shown in Paper I, a correlated pattern to the residuals can be seen for region 2. A similar pattern is also seen in the data for region 6.

We then fitted all the spectra with a cutoff power law. This function gives acceptable fits for all regions, and consistently gives better values of $\chi^2_p$. In Figure 10, we plot the residuals for the spectrum of region 2. These results, together with the steeper spectra detected with HXD, indicate the existence of a cutoff somewhere between the bandpasses of the XIS and HXD. Although statistically rejected for some regions, the results obtained with the power-law fits are consistent with previous studies with ASCA, Chandra, and XMM-Newton (Koyama et al. 1997; Slane et al. 1999; Uchiyama et al. 2003; Cassam-Chenaï et al. 2004; Hiraga et al. 2005). The results with Suzaku suggest that the photon index is larger and the absorption is smaller for the inner regions than for the outer regions. This tendency agrees with the radial profile shown in Figure 9. The difference of $N_H$ between the western bright spots and the inner region is $\Delta N_H \approx 0.3 - 0.4 \times 10^{22}$ cm$^{-2}$, which is consistent with the results from XMM-Newton. According to the discussion by Hiraga et al. (2005), there could be a correlation between the difference of $N_H$ and the presence of the molecular clouds in the western part of the SNR detected with the NANTEN telescope (Fukui et al. 2003; Moriguchi et al. 2005).

3.3. Broadband X-Ray Spectral Analysis

In this section, we connect the XIS and HXD spectra, which is crucial for a quantitative study of the cutoff structure and also for the multiwavelength study described in § 3.4. In order to study the general characteristics of the emission from RX J1713.7–3946, the XIS and HXD spectra obtained in § 3.2 and § 3.1 were co-added. Then, the summed XIS and HXD spectra were scaled to account for the flux from the whole remnant, which makes it easier not only to connect the XIS and HXD spectra but also to compare the combined spectrum directly to those of other wave-lengths in § 3.4. In scaling the spectra to the whole remnant, we assumed the surface brightness of the ASCA GIS image (1–5 keV) shown in Figure 1, the angular response of the XIS/XRT system (ARFs), and that of the HXD PIN presented in Figure 6 of Paper I. The relative normalization factor between XIS and HXD derived from Crab observations (Ishida et al. 2006) is included in the scaling. Therefore, the scaled XIS and HXD can be connected to each other without additional scaling if no systematic errors

![Figure 8](image_url) Comparison of the Suzaku XIS image and the gamma-ray image by the H.E.S.S. telescope (contours) taken from Aharonian et al. (2007), shown with color scale and green contours, respectively. The XIS image is same as Fig. 7b, but the scale is changed to stress the similarity of the two images.

![Figure 9](image_url) Radial profiles around the center of the SNR ($\alpha_{2000} = 17^h13^m33.6^s$, $\delta_{2000} = -39^\circ45'36''$) in the two energy bands. Each profile is normalized to its peak value for direct comparison. The radii corresponding the vertical dashed lines are shown in Fig. 7b with green dashed circles. [See the electronic edition of the Journal for a color version of this figure.]
are considered. However, we estimate that the normalization of the XIS and HXD spectra obtained by the procedures above should contain systematic errors of 10%–20%. In order to account for the systematic factor, we include a constant normalization factor and deal with this factor as a free parameter when fitting the XIS+HXD spectrum below. In this procedure, we discarded the HXD data from pointing 4, since they seem to be contaminated by a nearby hard X-ray source, as described in § 3.1.2.

Before the XIS and HXD spectra were jointly analyzed, each co-added spectrum was independently fitted using a power-law function. Table 4 summarizes the fit results. The HXD spectrum gives an acceptable fit. In contrast, the XIS does not, with a large probability value of $\chi^2$ for 711 degrees of freedom and residuals that begin to become large at $\sim 6$ keV. This fact is clearly seen in Figure 11, where the XIS and HXD spectra are plotted together with a power-law function which represents the XIS spectrum. The spectral steepening begins in the XIS band and continues smoothly into the HXD band. This plot strongly suggests that spectral steepening occurs around 10 keV. We have already reported such a spectral feature in Paper I for pointing 0 data. The same kind of feature has been revealed in this spectrum averaged over the SNR, which suggests that the spectral steepening is common in the entire region.

We then quantitatively evaluated the spectral steepening by fitting a model with a cutoff structure to the combined XIS+HXD spectrum. Below we use our numerically calculated synchrotron spectrum, which was embedded into the XSPEC package. As an electron distribution, we adopt a generalized form, namely,

$$\frac{dN_e}{dE} \propto E^{-3} \exp \left[ -\left( \frac{E}{E_{0}} \right)^{\beta} \right] ,$$

(2)

instead of taking a simple exponential cutoff often used in the literature. Here, $s$ represents index of electron spectrum, and $\beta(>0)$ determines rapidity of high-energy cutoff. The photon spectrum can be calculated as

$$\frac{dN}{d\varepsilon} \propto \varepsilon^{-1} \int F(\varepsilon/\varepsilon_c) \frac{dN_e}{dE} dE. \tag{3}$$

Here the function $F(\varepsilon)$ is defined as

$$F(\varepsilon) \equiv x \int_{\xi}^{\infty} K_{5/3}(\xi) d\xi, \tag{4}$$

where $K_{5/3}$ is the modified Bessel function of 5/3 order. When pitch angles are isotropic, the characteristic photon energy $\varepsilon_c$ is given as

$$\varepsilon_c = 0.543 \left( \frac{B}{100 \ \mu G} \right) \left( \frac{E}{10 \ \text{TeV}} \right)^2 \text{keV}. \tag{5}$$

The model consists of four parameters: $s$, $\Pi \equiv E_{0}^{1/2}$, $\beta$, and the flux normalization. Photon spectra were calculated and tabulated for reasonable ranges of the four parameters, to be used as an XSPEC table model. The parameters characterizing the electron energy distribution can be obtained directly from the fit to the X-ray data.

For RX J1713.7−3946, the most probable value for $s$ is 3.0 rather than 2.0, due to significant synchrotron cooling of electrons during the lifetime of the SNR $t_0$ (̴1000 yr). The electron spectrum becomes steeper by a factor of 1 ($s \rightarrow s + 1$) when the injection of electrons is constant and the lifetime $t_0$ is smaller than

![Fig. 10.—XIS (0.3−2.3 keV) spectrum from region 2. The lower panels show the residuals when the spectrum is fitted with a power law and a power law with an exponential cutoff.](image-url)
the timescale of synchrotron cooling, \( t_{\text{sync}} \). Since \( t_{\text{sync}} \) can be written as

\[
t_{\text{sync}} = 28 \left( \frac{B}{100 \, \mu G} \right)^{-3/2} \left( \frac{\varepsilon}{3 \, \text{keV}} \right)^{-1/2} \text{yr},
\]

the condition above is satisfied in the energy range

\[
\varepsilon > \varepsilon_b \equiv 2.3 \left( \frac{B}{100 \, \mu G} \right)^{-3} \left( \frac{t_0}{10^3 \, \text{yr}} \right)^{-2} \text{eV}.
\]

To explain the variability of X-ray emission reported on a year timescale from compact regions of the shell of RX J1713.7−3946, Uchiyama et al. (2007) proposed that the magnetic field in these compact regions is amplified to 1 mG. The average large-scale magnetic field in the remnant should be significantly lower, but even for \( B \approx 100 \, \mu G \) the above condition in the X-ray domain is safely satisfied. Therefore, for a strong shock with a compression ratio of 4.0, the index of X-ray-emitting electrons should be close to \( s = 3.0 \).

We fitted the Suzaku spectrum with the synchrotron spectrum described above. In the fitting procedure, we fixed the electron index \( s \). Table 4 summarizes the result for the case of \( s = 3.0 \), which corresponds to the most probable case following the discussion above. We also present results for \( s = 2.0 \), for comparison. This case can be realized if the magnetic field and/or the age of the remnant are much smaller than we expect, as seen in equation (7). The spectral fitting with the electron index of \( s = 3.0 \) yields rather rapid steepening with \( \beta = 3.4^{+0.7}_{-0.5} \) compared to the conventionally used exponential cutoff. However, one should be careful with the physical interpretation of the fit based on equation (2).

Indeed, while the electron spectrum is derived from the broadband Suzaku X-ray data assuming a specific spectral form given by equation (2), curve 1 in Figure 12 has a more general meaning. It does not depend on the assumed analytical presentation, and in fact relates uniquely the energy spectrum of electrons to the measured X-ray spectrum. Indeed, curve 1 can be presented in different mathematical forms. In particular, the electron spectrum shown by curve 1 in Figure 12 is quite close to the theoretical prediction for the spectrum of shock-accelerated electrons in a young SNR (Zirakashvili & Aharonian 2007),

\[
\frac{dN_e}{dE} \propto E^{-\beta} \left[ 1 + 0.66 \left( \frac{E}{E_0} \right)^{5/2} \right]^{9/5} \exp \left[ -\left( \frac{E}{E_0} \right)^2 \right].
\]

This spectrum is derived under the assumption that electrons are accelerated by a strong shock in the Bohm diffusion regime and that the energy losses of electrons are dominated by synchrotron cooling. It can be seen that the energy spectrum below the cutoff is described by a function which deviates from a pure power-law form, by an exponential term with \( \beta = 2 \). The latter has a simple physical interpretation and is a result of combination of two effects: acceleration in the Bohm diffusion regime, and energy losses in the synchrotron regime. Curve 2 shown in Figure 12 is calculated for the parameter \( \Pi = E_0 B^{1/2} = 201 \, \text{eV} \mu G^{1/2} \).

The energy spectrum of synchroton radiation corresponding to the electron spectrum given by equation (8) has the form (Zirakashvili & Aharonian 2007)

\[
\frac{dN}{d\varepsilon} \propto \varepsilon^{-2} \left[ 1 + 0.46 \left( \frac{\varepsilon}{\varepsilon_0} \right)^{0.6} \right]^{2.29} \exp \left[ -\left( \frac{\varepsilon}{\varepsilon_0} \right)^{1/2} \right].
\]

This spectrum fits well the broadband Suzaku X-ray data for a single parameter, \( \varepsilon_0 = 0.67 \pm 0.02 \) keV. Note that the exponential term in the synchrotron spectrum is a weak function of energy (\( \propto \exp \left[ -\left( \varepsilon/\varepsilon_0 \right)^{1/2} \right] \)); therefore, the characteristic energy \( \varepsilon_0 \) can formally only be considered as the cutoff energy. In fact, for the shape given by equation (9), the break in the spectrum starts at much higher energies (\( \varepsilon \approx 10\varepsilon_0 \)).

3.4. Multiwavelength Study

3.4.1. Spectral Energy Distribution

The high-quality data of Suzaku, obtained over two decades in energy and combined with the TeV gamma ray data, allow definite conclusions concerning the origin of multi-TeV parent particles based on the comparison of model predictions with observations. In particular, it is important that the Suzaku data provide unambiguous information about the shape of the energy spectrum of electrons in the cutoff region.

Figure 13 shows the spectral energy distribution (SED), \( E^2 dN/dE \), of RX J1713.7−3946 from radio to TeV energies. The
X-ray data correspond to the entire remnant; they are reconstructed assuming the best-fit model given by equation (9), corrected for the interstellar absorption with $N_{\text{H}} = 0.70 \times 10^{22}$ cm$^{-2}$. The points in the TeV gamma-ray range corresponding to the fluxes of the whole remnant are from the latest report of the H.E.S.S. collaboration (Aharonian et al. 2007). The EGRET upper limit is taken from Aharonian et al. (2006); it is obtained through modeling and subtracting the resolved EGRET source 3EG 1714–3857 (Hartman et al. 1999). The two data points in the radio band are shown as measured with the ATCA telescope (Lazendic et al. 2004). However, it should be noted that these fluxes are detected only from the NW rim region; therefore, they should be treated as lower limits when compared to model predictions for the whole remnant. The recent estimates based on observations with ATCA and the 30 m radio telescope IRA show that the flux of the entire remnant is fixed to 3.0. Curve 2 is the model by Zirakashvili & Aharonian (2007). Both the electron spectrum obtained by fitting the Suzaku spectrum with a synchrotron spectrum assuming the electron distribution given by eq. (2) when $\gamma$ is fixed to 3.0. Curve 2 is the model by Zirakashvili & Aharonian (2007). Both the spectra are drawn by assuming the best-fit parameters of the Suzaku spectrum, which are shown in Table 5. Curve 3 is the exponential cutoff spectrum often assumed in the literature. The cutoff energy is set to the same value as that of curve 1.

### Table 5

| Assumed Function | $N_{\text{H}}$ ($10^{22}$ cm$^{-2}$) | $N_{\text{H}}$ (Constant) | Parameter(s) | $F_{1-10\text{keV}}$ (10$^{-9}$ erg s$^{-1}$ cm$^{-2}$) | $\chi^2$ ($\nu$) |
|------------------|----------------------------------|--------------------------|--------------|----------------------------------|-----------------|
| Electron distribution of eq. (2)$^b$ | $0.71 \pm 0.01$ | $1.03 \pm 0.06$ | $s = 3.0$ (fixed), $\beta = 3.4^{+0.7}_{-0.5}$, $\Pi = 402 \pm 6$ TeV $\mu$G$^{-1/2}$ | $7.2 \pm 0.1$ | 1.11 (778) |
| $0.68 \pm 0.01$ | $1.03^{+0.05}_{-0.05}$ | $s = 2.0$ (fixed), $\beta = 1.5 \pm 0.2$, $\Pi = 207^{+21}_{-20}$ TeV $\mu$G$^{-1/2}$ | $7.1 \pm 0.1$ | 1.07 (778) |
| Z&A (2007)$^c$ | $0.70 \pm 0.01$ | $1.08 \pm 0.04$ | $\varepsilon_0 = 0.67 \pm 0.02$ keV | $7.2 \pm 0.1$ | 1.11 (779) |

*Note:* Errors represent 90% confidence.

$^a$ Corrected for absorption.

$^b$ Details of the calculation of synchrotron spectrum is described in the text.

$^c$ A model by Zirakashvili & Aharonian (2007), the synchrotron spectrum of which is shown as eq. (9) in this paper.
The electrons suffer synchrotron losses; thus, the electron spectrum above a certain energy becomes steeper \[ E^{-\delta} \rightarrow E^{-(\delta+1)} \]. The position of the break in the electron spectrum appears at

\[
E_0 = 1.25 \left( \frac{B}{100 \, \mu G} \right)^{-2} \left( \frac{t_0}{10^3 \, yr} \right)^{-1} \, \text{TeV}. \quad (10)
\]

For a magnetic field \( B = 200 \, \mu G \) and age of the source \( t \leq 1000 \, yr \), the spectral break in the synchrotron spectrum corresponding to the transition of the electron spectrum from an uncooled to a cooled regime appears around 1 eV (see Fig. 13). Thus, for young SNRs the detection of the synchrotron break at optical/infra-red wavelengths would be an additional argument in favor of strong magnetic field. The cooling break in the electron spectrum is also reflected in the gamma-ray band. Namely, for \( B = 200 \, \mu G \) the corresponding signature in the IC gamma-ray spectrum appears around 10 GeV. Unfortunately (see Fig. 13), for such a strong magnetic field, the IC component is suppressed, and falls well below the sensitivity of gamma-ray detectors in this energy band, including GLAST. In the presence of such a strong magnetic field, the only viable mechanism that can produce TeV gamma-rays at the flux level detected by H.E.S.S. is related to interactions of ultrarelativistic protons with ambient gas through production and decay of \( n^0 \)-mesons. To explain the detected flux of gamma-rays, protons should be accelerated to energies well beyond 100 TeV, and the parameter \( A = (W_p/10^{50} \, \text{erg})(n/1 \, \text{cm}^{-3})(d/1 \, \text{kpc})^{-2} \) should be between 1.5 and 3, depending on the spectrum of the protons.

In order to increase the IC flux to the level of the observed TeV gamma-ray flux, the magnetic field should be reduced down to 10 and 15 \( \mu G \). For the given magnetic field, the high-quality X-ray data of Suzaku obtained over two energy decades allow derivation of the electron spectrum with high accuracy within the interval covering one energy decade: from \( \sim 50(B/10 \, \mu G)^{-1/2} \) TeV to \( \sim 500(B/10 \, \mu G)^{-1/2} \) TeV. This allows us to calculate the spectrum and absolute flux of IC gamma rays above a few TeV without any model assumptions, as long as the main target for the IC gamma-ray production remains the 2.7 K CMB. The contribution of the diffuse optical/infra-red radiation fields is generally less, although the optical photons may provide enhanced TeV emission at low, sub-TeV energies. For calculations of the IC spectrum, we used the interstellar radiation model of Porter et al. (2006), who proposed a significantly larger flux of optical and infrared components compared to the generally accepted flux. However, the results presented in Figure 14 show that even this high diffuse optical and infrared radiation fails to account for the observed gamma-ray flux below a few TeV. In order to fill this gap, one needs to assume an unreasonably large density of optical radiation. This is demonstrated in Figure 15, where an agreement of IC calculations with the reported gamma-ray fluxes is achieved assuming an additional, although in our view quite unrealistic, component of optical radiation with a density of 140 eV cm\(^{-3}\).

It should be noted that the problem of explaining the low-energy gamma rays in Figure 14 is related to the large energy of the break in the electron spectrum given by equation (10), and correspondingly to the position of the Compton peak which appears above 1 TeV in the SED of gamma rays. Thus, the reduction of the break energy down to 200 GeV could in principle solve the problem. However, since the magnetic field in this model cannot exceed 15 \( \mu G \), the only way to shift the Compton peak to sub-TeV energies is to assume that the supernova remnant is older than 10\(^4\) yr.

An alternative solution for explaining the gamma-ray data within the IC models is to assume a higher density of relativistic electrons responsible for \( \lesssim 1 \) TeV gamma rays, i.e., to postulate a second, low-energy electron component in the shell. Formally, this assumption does not a priori contradict the observations, since the additional electrons are required to be present below 20 TeV, i.e., in the energy range that is not constrained by Suzaku observations (for production of the lowest energy X-rays detected by Suzaku in a magnetic field of 15 \( \mu G \), the electron energy must exceed 40 TeV). The results calculated under such assumption are shown in Figure 16. The second electron component is assumed to have a power-law injection spectrum with the same index as the first (main) component, \( s = 2.0 \), but with a high-energy cutoff around 10 TeV. The latter is required to prevent conflict with the observed gamma-ray spectrum above 1 TeV.

### 3.4.2. Morphology

A comparison between the X-ray and the TeV gamma-ray morphology is expected to provide information about the acceleration/emission processes. As shown in Figure 8, the Suzaku XIS image revealed a significant correlation with that of H.E.S.S. telescopes, not only in the bright structures but also in the dim regions.
of the remnant. In the following discussion, the two images are compared with each other on a more quantitative basis. It should be taken into account that the X-ray morphology can be affected by the spatial distribution of absorption column density, $N_H$. In order to avoid this effect, here we disregard the energy band below 1 keV, and use two energy intervals, 2–5 keV and 5–10 keV, for comparison. For the $N_H$ variation as shown in Table 3, the count rate can vary by 5% and 0.7% in the 2–5 keV and 5–10 keV bands, respectively. One should also take into account the difference of point-spread functions between the Suzaku XIS and H.E.S.S. when comparing the two images. To prevent this, we compare surface brightness for each square region with a size of $10.8' \times 10.8'$, which is larger than the point-spread functions of either observatory. The regions are indicated with green dashed lines in Figure 17.

Figure 18 shows a scatter plot between the Suzaku XIS count rate ($F_{\text{keV}}$) and that of H.E.S.S. ($F_{\text{TeV}}$). As seen in this plot, the X-ray count maps correlate strongly with the gamma-ray count map. The correlation coefficients are calculated to be 0.85 and 0.83 for the 2–5 keV and 5–10 keV bands, respectively. It is worth noting that there are some deviations (X-ray intensity excesses) in the bright regions. Figure 19 shows a map of $F_{\text{keV}} - F_{\text{TeV}}$ (for the 2–5 keV band) overlaid with the H.E.S.S. contours, in which one can see that the X-ray excesses are present along the NW and SW rims.

4. DISCUSSION

4.1. Cutoff in the Synchrotron Spectrum

We conducted a series of Suzaku observations which cover about two-thirds of the surface of SNR RX J1713.7–3946. Through the data analysis, we successfully detected signals up to $\sim$40 keV from each of the pointings. The HXD spectra above 10 keV are significantly steeper than those obtained from the XIS below 10 keV, suggesting that a spectral cutoff is common throughout the remnant. By combining the XIS and HXD spectra, we obtained a wide-band spectrum with high statistics, which clearly shows a cutoff around 10 keV.

Taking advantage of the high photon statistics, we performed a detailed study of the cutoff shape and compared it with a recent theoretical prediction by Zirakashvili & Aharonian (2007). A sharp cutoff of the accelerated electron spectrum is needed to reproduce the cutoff shape in the synchrotron spectrum detected with Suzaku. The spectrum of electrons derived from Suzaku data is in good agreement with the analytical model of Zirakashvili & Aharonian (2007).

The cutoff energy in the spectrum of synchrotron radiation contains important information about the efficiency of diffusive shock acceleration. For acceleration in the Bohm diffusion regime and when energy losses of electrons are dominated by synchrotron cooling, the cutoff energy, $\varepsilon_0$ in equation (9) is expressed as

$$\varepsilon_0 = 0.55 \left( \frac{v_s}{3000 \text{ km s}^{-1}} \right)^2 \eta^{-1} \text{keV},$$

(11)

where $v_s$ is the shock speed and $\eta$ ($\geq 1$) is the so-called “gyrofactor.” The case of $\eta = 1$ corresponds to the “Bohm limit,” and implies high level of turbulence, $8B \sim B$. The Suzaku spectrum is characterized by the best-fit parameter $\varepsilon_0 = 0.67$ keV, which gives $v_s = 3300\eta^{1/2}$ km s$^{-1}$. Here, we assume that the shock speed $v_s$ is uniform throughout the remnant, which is supported by...
the fact that the outer boundary of the X-ray morphology is nearly circular. The upper limit of the shock speed, $v_s \leq 4500 \, \text{km} \, \text{s}^{-1}$, derived from the Chandra data (Uchiyama et al. 2007), results in $\eta \leq 1.8$. This is a strong evidence of acceleration of electrons in the regime close to the Bohm limit. Note that a similar result was obtained for the SW rim of the remnant in Uchiyama et al. (2007). Here we confirm this conclusion for a larger area of the remnant with higher statistics.

4.2. Multiwavelength Spectrum

While there is little doubt as to the synchrotron origin of broadband X-ray emission measured by Suzaku, the X-ray spectrum alone does not give preference to the strength of the magnetic field in the region of production of synchrotron radiation. Formally, the field can be as small as 10 $\mu$G and as large as 100 $\mu$G. Meanwhile, the strength of the magnetic field has a dramatic impact on the origin of TeV gamma-rays. The so-called leptonic or inverse Compton models require magnetic fields between 10 $\mu$G and 15 $\mu$G. Even so, it is difficult to achieve, at least within a simple one-zone model, a satisfactory explanation of both X-ray and TeV gamma-ray spectral features, unless we invoke an extremely high diffuse radiation field of optical photons to enhance the IC gamma-radiation below 1 TeV (see Fig. 15). A more realistic approach to explaining the broadband TeV gamma-ray spectrum within IC models can be realized by assuming the existence an additional, low-energy electron component in the shell (see Fig. 16). Even so, the most serious problem for IC models remains the requirement of low magnetic field in the gamma-ray production region, in contrast to large magnetic field required to explain the fast variability of X-ray emission on small scales. Formally, one may assume that gamma-rays are mainly produced in “voids,” i.e., in regions with very low magnetic field. This would imply quite an inhomogeneous distribution of the magnetic field in the shell. One the other hand, the observed strong X-ray and TeV correlation within the IC models can be explained only if there is a homogeneous distribution of magnetic field.

The large-scale magnetic fields on parsec scales with an average strength larger than $\geq 15 \, \mu$G make the IC gamma-ray production inefficient, and thus gives preference to the so-called hadronic models of gamma-rays produced at interactions of accelerated protons with the ambient gas via production and decay of secondary $\pi^0$-mesons. X-rays are produced, as in leptonic models, by synchrotron radiation of directly accelerated electrons. This is demonstrated in Figure 13 for very strong magnetic field, $B = 200 \, \mu$G. Note that while comparing the model predictions with measurements in the radio band, one should take into account that the radio points shown correspond to measurements of NW rim, while the X-ray and gamma-ray points are for the entire remnant. If the ratio of the radio flux from the NW rim to that from the whole remnant is not very different from the corresponding ratio in X-rays, the flux from the whole SNR should be significantly larger. This would reduce the difference between the measurements and predictions. In any case, the radio flux can be significantly reduced assuming a somewhat smaller magnetic field or harder electron spectrum. Indeed, in Figure 20 we show model calculations performed for a magnetic field $B = 100 \, \mu$G. While the synchrotron X-ray flux is described perfectly as before (in Fig. 13), the radio flux is lower by a factor of 4; at 1.4 GHz it is 34 Jy, which is close to the latest estimates of radio flux from the whole remnant based on observations with ATCA and the 30 m radio telescopes of IRA (F. Acero et al. 2008, in preparation; G. Dubner 2008, private communications).

The radio flux can be suppressed even for an ambient field larger than 100 $\mu$G, provided that the electron injection spectrum is harder than $E^{-2}$. Figure 21 demonstrates this possibility, where we assume an electron/proton index of $s = 1.7$, which corresponds to a compression ratio of $\sigma = 5.3$. Note that $\sigma$ can exceed the adiabatic upper limit of 4 as described by Berezhko & Völk (2006). Note also that the value of $s = 1.7$ is consistent with the conclusion of Villante & Vissani (2007) based on semianalytical derivation of the parent proton spectrum from the H.E.S.S. data. In model calculations shown in Figure 21, the spectrum of protons requires an “early” exponential cutoff at $E_{p0} = 25.0 \, \text{TeV}$. Formally, the spectral index $s = 1.7$ implies shock acceleration in the nonlinear regime, which in fact predicts some deviation from a pure power-law distribution of accelerated particles (see, e.g.,
Ellison et al. 2007; Berezhko & Völk 2006). This would lead to a further reduction of the radio flux.

The convection of low-energy electrons could be another reason for low radio flux. Note that the escape of electrons through convection has a strong impact only on low-energy electrons; because of fast synchrotron cooling, the effect of escape is negligible for multi-TeV electrons. A significant quantity of low-energy electrons can escape from the shell of the SNR before emitting radio photons. Therefore, the radio flux can be reduced while the X-ray flux will remain unchanged.

For calculations shown in Figure 13, the total energy of electrons is estimated as \( W_e = 3.1 \times 10^{46} \text{(d/1 kpc)}^2 \text{erg} \), and the energy for protons as \( W_p = 2.7 \times 10^{50} (n/1 \text{ cm}^{-3})^{-1} (d/1 \text{ kpc})^2 \text{erg} \). For higher energy spectra with power-law index \( s = 1.7 \), corresponding to Figure 21, one has \( W_e = 6.0 \times 10^{45} (d/1 \text{ kpc})^2 \text{erg} \), and \( W_p = 1.6 \times 10^{50} (n/1 \text{ cm}^{-3})^{-1} (d/1 \text{ kpc})^2 \text{erg} \), respectively. The proton/electron ratio in either case is very small, \( K_{ep} \leq 10^{-4} (n/1 \text{ cm}^{-3}) \). This value is significantly smaller than that for directly observed local cosmic rays (\( K_{ep} \approx 0.01 \)), unless a large ambient matter density of \( n \approx 100 \text{ cm}^{-3} \) is assumed. Katz & Waxman (2008) and Butt et al. (2008) have argued that the hadronic scenario for this SNR presents difficulties because the \( K_{ep} \) value should be consistent with local cosmic rays and other SNRs. However, the \( K_{ep} \) value of one SNR at a fixed age does not necessarily need to agree with the local cosmic ray value. The low-energy electrons are likely produced in later stages of SNR evolution, when the \( K_{ep} \) value can be different from the present value. A comparison with other SNRs should be performed with care as well.

Cutoff energy in the gamma-ray spectrum should give an important hint whether SNRs are sources of cosmic rays below the knee, if gamma rays observed by H.E.S.S. have hadronic origins. Plaga (2008) argued that the cutoff energy of the H.E.S.S. spectrum of RX J1713–3946 is around 18 TeV, which can be translated to a proton energy more than 10 times below the energy of the knee. Indeed, our multiwavelength study requires a cutoff in the proton spectrum around 100 TeV or even less for a hard acceleration spectra of protons. However, one should take into account that even in the case of effective acceleration, the highest energy protons beyond 100 TeV escape the source in quite short timescales, and hence do not contribute to the gamma-ray production at the present epoch (Ptuskin & Zirakashvili 2005; Gabici & Aharonian 2007).

A unique feature of RX J1713.7–3946 is the lack of thermal X-ray emission. Recently, Katz & Waxman (2008) and Butt et al. (2008) interpreted this fact as an argument against the hadronic model for TeV gamma rays. Generally it is true that plasma in young supernova remnants is heated to high temperatures, observed via thermal X-ray emission of hot electrons. However, one should take into account that we deal with a unique object, and the lack of thermal X-ray emission cannot a priori be invoked as an argument against the hadronic origin of the observed TeV gamma rays.

It is important to note that in SNR shocks the formation of high plasma temperatures with \( kT_i = (3/16) m_i c^2 \) is relevant only to protons (ions), and that a high ion temperature does not automatically (from first principles) mean a high electron temperature. In fact, the only known heating process of thermal electrons is Coulomb collisions between electrons and protons (ions), which, however, has too long a timescale to establish electron-proton equipartition. On the other hand, we do know from X-ray observations that the electrons in young SNRs are heated to keV temperatures. This can be explained by assuming that a hypothetical mechanism, most likely related to the energy exchange through excited plasma waves, is responsible for effective electron heating in SNRs. As long as the nature of this mechanism in collisionless shocks remains unknown, one cannot predict, even qualitatively, the specifics of its operation on a source by source basis.

We indeed deal with two interesting facts. First, many young SNRs, such as Tycho and Cassiopeia A, with intense thermal X-ray emission and intense nonthermal radio emission, emit little (or none) in TeV gamma rays. On the other hand, RX J1713.7–3946, with lack of (or rather very low) thermal X-ray emission and with relatively weak nonthermal radio emission, is a source of powerful TeV radiation. These two facts can be treated as a hint for the low efficiency of establishing equipartition in the thermal plasma in very effective TeV particle accelerators such as RX J1713.7–3946. It is interesting to note in this regard that a similar tendency is also found for another effective TeV accelerator, SN 1006 (Vink et al. 2003). Whether the reduction of the exchange rate between different particle species in thermal plasma has a link to the particle acceleration in high Mach number shocks, as proposed by Vink et al. (2003), is a very interesting question to be explored in future deep theoretical and phenomenological
become dominated by the acceleration of fresh material swept up by the shock wave. However, for the electrons, the energy-dependent diffusion coefficient implies that the electron temperature derived from their spectral analysis is 0.5 keV, which is far below the prediction. According to their discussion, not only electron heating but also ion heating is suppressed, and a substantial fraction of energy may be going into cosmic-ray production due to the nonlinear effects in the shock.

The nonlinear shock acceleration in this object can convert a significant fraction, up to \( f \sim 0.5 \), of the kinetic energy of explosion into relativistic particles. Correspondingly, the fraction of available energy that goes to the heating of the ambient plasma will be reduced to \( 1 - f \sim 0.5 \). Yet, conservative estimates show that plasma in RX J1713.7–3946 can be heated to quite high temperatures even though the heating of electrons and protons proceeds only through Coulomb exchange. This question has recently been studied by Ellison et al. (2007) for a standard SNR of age \( t_{\text{SNR}} = 500 \) yr and energy \( E_{\text{SN}} = 10^{51} \) erg. In particular, it has been shown that in the case of effective diffusive shock acceleration and plasma density \( n = 0.1 \) cm\(^{-3}\), the ratio of synchrotron luminosity to thermal (bremsstrahlung) luminosity can be as large as 100. This implies that in the case of RX J1713.7–3946, from which thermal X-ray emission is not observed, the plasma density cannot significantly exceed 0.1 cm\(^{-3}\) (the luminosity of thermal bremsstrahlung is proportional to \( n^2 \)). The low density, of order of 0.1 cm\(^{-3}\), reduces the parameter space for hadronic models, but does not exclude it. Indeed, as mentioned above, the TeV gamma-ray flux of RX J1713.7–3946 can be explained by interactions of protons if the parameter \( A = \left( W_p / 10^{50} \text{ erg} \right) (n/1 \text{ cm}^{-3}) (d/1 \text{ kpc})^{-2} \) exceeds 1.5–3, depending on the spectrum of protons. Assuming that more than 30% of the explosion energy of this SNR is released in accelerated protons, and that the plasma in the gamma-ray production region is compressed by a factor of a few, we find that the location of the source at a distance of about 1 kpc would marginally support the hadronic model. While a closer location of the source would make the model requirements quite viable and flexible, a location of the source beyond 1 kpc seems unreasonable, considering the upper limit on the shock speed of 4500(d/1 kpc) km s\(^{-1}\) given by Uchiyama et al. (2007).

Finally, we should mention the model suggested by Malkov et al. (2005), which can naturally explain both the low synchrotron flux at radio frequencies and the lack of thermal X-ray emission of RX J1713.7–3946. The standard scenarios of gamma-ray production in SNRs assume that radiation is produced downstream, where the density of both relativistic particles and thermal plasma is higher than upstream. However, in the cases when the shock is expanding into a low-density wind bubble and approaching cold dense material, e.g., a swept-up shell or surrounding molecular clouds, the gamma-radiation is contributed predominantly from upstream. While the energy distribution of accelerated particles downstream is coordinate-independent in both linear and nonlinear regimes, the particle distribution upstream is coordinate-dependent. Because of the energy-dependent diffusion coefficient, the high-energy particles diffuse ahead of low-energy particles, and thus a dense material adjacent upstream will “see” relativistic particles (protons and electrons) with low-energy exponential cutoff, \( E_{\text{min}} \), which depends on the location of the dense regions. This implies that the effective production of TeV gamma-rays (from \( p-p \) interactions) and X-rays (from synchrotron radiation of TeV electrons) will be not accompanied by low-energy (GeV) gamma-rays and synchrotron radio emission. Obviously, this model is not constrained by lack of thermal emission.

4.3. Morphology

In addition to the spectral information, the comparison of X-ray and TeV gamma-ray images presented in Figure 18 helps us to draw the physical picture of RX J1713.7–3946. Let us first discuss the tight correlation observed in most parts of the remnant. Within the hypothesis of a hadronic origin of gamma-rays, the gamma-ray flux is proportional to the number densities of the ambient matter and relativistic protons, while the X-ray flux is proportional to the number density of electrons. If the matter distribution varies significantly throughout the SNR, we need fine parameter tuning among the matter distribution, the electron injection rate, and the proton injection rate, in order to produce the tight correlation. Therefore, a more natural explanation is that the matter density is uniform, and that the injection rates of electrons and protons are proportional to each other.

The X-ray flux excess along the NW and SW rims provides a unique probe of recent acceleration activity. Let us consider a “toy” model and compare its predictions with the observational results. In the toy model, the injection rate of electrons and protons keeps constant, but increases by a factor of 1.5 in the last 10 yr only at the NW and SW rims. What is important here is the difference in cooling times between electrons and protons. The synchrotron cooling time of an electron emitting synchrotron photons with energy of \( \varepsilon \) is given as equation (6), while the cooling time of protons due to \( p-p \) interactions can be expressed as

\[
\tau_{pp} = 5.3 \times 10^7 \left( \frac{n}{1 \text{ cm}^{-3}} \right)^{-1} \text{ yr}
\]  

and is almost energy-independent. For the magnetic field \( B = 100 \) \( \mu \text{G} \), the cooling times of electrons emitting 2 and 5 keV
X-rays are 12 and 7.6 yr, respectively. For any reasonable density of ambient gas, the cooling time of protons is much longer than the lifetime of this SNR. While the synchrotron X-rays we observe at present are emitted by electrons accelerated during the last ~10 yr, the flux of \( \pi^0 \)-decay gamma rays is provided by protons accelerated throughout the lifetime of the SNR. Figure 22 shows the scatter plot of \( F_{\text{keV}} \) and \( F_{\text{TeV}} \) expected from the toy model, which shows a distribution similar to the observational results in Figure 18. The recent active acceleration increases the X-ray flux, while keeping the gamma-ray flux almost unchanged.

5. SUMMARY

We observed SNR RX J1713.7–3946 with the Suzaku observatory. Hard X-rays up to ~40 keV are detected from each of the 11 pointings. The hard X-ray morphology estimated by the HXD PIN data is generally consistent with that extrapolated in the energy region below 10 keV. When the HXD spectra are fitted with a power law, the photon indices are larger than those obtained from the XIS data. The difference in photon indices between the XIS and the HXD varies from region to region. Although this may suggest a variation of spectral shape or cutoff energy, the FoV of the HXD PIN is not small enough to allow detailed imaging spectroscopy. Such studies will become possible with upcoming missions with hard X-ray mirrors, such as NeXT, NuSTAR, or Symbol-X. Moreover, these missions will extend the effective studies up to 100 keV. If the TeV gamma-ray emission of RX J1713.7–3946 is of hadronic origin, this should allow detection and study of synchrotron X-ray emission of electrons produced in proton-proton interactions via decays of secondary charged pions (Aharonian 2004). In this regard, the above-mentioned missions could provide very effective tools for deep (at levels as low as \( 10^{-13} \) erg cm\(^{-2}\) s\(^{-1}\) ) probes of hadronic processes in SNRs in the \( \geq 100 \) TeV energy regime with unprecedented (subarcminute) angular resolution.

Using the XIS and HXD data, we obtained a synchrotron spectrum in the energy range of two decades (0.4–40 keV), which means that we can probe the parent electron distribution in the energy range of one decade regardless of the magnetic field strength. The wide-band coverage enables us to see a clear high-energy range of one decade independent of the magnetic field means that we can probe the parent electron distribution in the remnant. This excess can be explained by recent activity accompanied by effective acceleration of electrons in localized regions of the shell.

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