NON-THERMAL X-RAYS AND INTERSTELLAR GAS TOWARD THE $\gamma$-RAY SUPERNOVA REMNANT RX J1713.7$-$3946: EVIDENCE FOR X-RAY ENHANCEMENT AROUND CO AND H\textsc{i} CLUMPS

H. Sano$^{1}$, T. Tanaka$^{2}$, K. Torii$^{3}$, T. Fukuda$^{1}$, S. Yoshiike$^{4}$, J. Sato$^{5}$, H. Horachi$^{6}$, T. Kuwahara$^{1}$, T. Hayakawa$^{1}$, H. Matsumoto$^{1}$, T. Inoue$^{1}$, R. Yamazaki$^{3}$, S. Inutsuka$^{1}$, A. Kawamura$^{1,4}$, K. Tachihara$^{1}$, H. Yamamoto$^{1}$, T. Okuda$^{1}$, N. Mizuno$^{1,4}$, T. Onishi$^{1,5}$, A. Mizuno$^{6}$, and Y. Fukui$^{1}$

1 Department of Physics, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan; sano@aph.nagoya-u.ac.jp
2 Department of Physics, Kyoto University, Kitashirakawa-owake-cho, Sakyo-ku, Kyoto 606-8502, Japan
3 Department of Physics and Mathematics, Aoyama Gakuin University, Fuchinobe, Chuo-ku, Sagamihara 252-5258, Japan
4 National Astronomical Observatory of Japan, Mitaka 181-8588, Japan
5 Department of Astrophysics, Graduate School of Science, Osaka Prefecture University, 1-1 Gakuen-cho, Naka-ku, Sakai 599-8531, Japan
6 Solar-Terrestrial Environment Laboratory, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan

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ABSTRACT

RX J1713.7$-$3946 is the most remarkable very high energy $\gamma$-ray supernova remnant that emits synchrotron X-rays without thermal features. We made a comparative study of CO, H\textsc{i}, and X-rays in order to better understand the relationship between the X-rays, and the molecular and atomic gas. The results indicate that the X-rays are enhanced around the CO and H\textsc{i} clumps on a pc scale, but are decreased inside the clumps on a 0.1 pc scale. Magnetohydrodynamic numerical simulations of the shock interaction with molecular and atomic gas indicate that the interaction between the shock waves and the clumps excite turbulence, which amplifies the magnetic field around the clumps. We suggest that the amplified magnetic field around the CO and H\textsc{i} clumps enhances the synchrotron X-rays and possibly the acceleration of cosmic-ray electrons.

Key words: cosmic rays – ISM: clouds – ISM: individual objects (RX J1713.7$-$3946) – ISM: supernova remnants – X-rays: ISM

Online-only material: color figures

1. INTRODUCTION

RX J1713.7$-$3946 is one of the most prominent supernova remnants (SNRs) emitting high-energy radiation covering the $\gamma$-rays and X-rays, which are likely emitted by cosmic-ray (CR) particles accelerated in the SNR via diffusive shock acceleration (DSA; e.g., Bell 1978; Blandford & Ostriker 1978). The SNR is located relatively close to the Galactic center at $(l, b) = (347^\circ.3, -0^\circ.5)$, where contamination by the Galactic foreground/background is heavy at any wavelength. The SNR was not known as an SNR in the radio continuum emission and SNR were discovered and mapped by the atmospheric Cerenkov telescopes (Enomoto et al. 2002; Aharonian et al. 2004, 2006a, 2006b, 2007). In particular, the H.E.S.S. observations resolved that the $\gamma$-ray distribution is shell-like with a diameter of 1$^\circ$ by 0$^\circ.1$ point spread function. Since the $\gamma$-rays are detected at an energy range of 1$-$10 TeV, the CR protons producing the $\gamma$-rays may reach an energy range of 10$-$800 TeV, which is close to the knee, if the hadronic origin is working. The SNR is therefore an important candidate for where the acceleration of the high-energy CR protons is best tested in the Galaxy. It is noteworthy that the X-rays of the SNR are a purely non-thermal synchrotron emission, indicating that the CR electrons are accelerated in the SNR up to the 10 TeV range; there are only two SNRs in addition to RX J1713.7$-$3946 that show such non-thermal X-rays, RX J0852.0$-$4622 (Vela Jr.) and HESS J1731$-$347, known to date (e.g., Koyama et al. 1997; Slane et al. 2001; Tian et al. 2010). Detailed theoretical modeling of this high-energy radiation has been made over a wide range of physical parameters appropriate for the SNR, and has shown that the observed properties of high-energy radiation are reproduced under reasonable sets of physical parameters relevant for the CR acceleration (e.g., Zirakashvili & Aharonian 2007, 2010). It is thus becoming more and more important to constrain observationally the physical parameters of the SNR, like the magnetic field, and their distributions.

It is now well established that the SNR is located 1 kpc from us as first determined by the radial velocity of the associated CO molecular gas at $-7$ km s$^{-1}$ in V$\text{L}\text{SR}$ (Fukui et al. 2003). This distance is confirmed by subsequent observations in X-rays and CO (Cassam-Chena"{i} 2004; Moriguchi et al. 2005). Moriguchi et al. (2005) showed further details of the $^{12}$CO($J = 1$–0) distribution and confirmed the interacting molecular gas identified by Fukui et al. (2003). At 1 kpc, it is most likely that the SNR corresponds to the historical SNR SN 393 with an age of 1600 yr (Wang et al. 1997). Sano et al. (2010, hereafter Paper I) presented a comparison of the X-rays and the CO in $^{12}$CO($J = 2$–1, 4–3) transitions for the western rim of the SNR, where the most prominent millimeter/submillimeter CO clumps are distributed. These authors found that a dense CO clump named “peak C” was a site of low-mass star formation and was surrounded by bright X-rays at a pc scale, and that the CO clump showed an anti-correlation with the X-rays at a sub-pc scale. According to the magnetohydrodynamic (MHD) numerical simulations (Inoue et al. 2012), the SNR shock–cloud interaction excites turbulence in highly inhomogeneous interstellar medium (ISM), which leads to amplification of the magnetic field around dense clumps. These observational and theoretical results suggest that the magnetic field becomes stronger around dense clumps in the SNR, leading to bright X-rays at a pc scale around them, whereas the X-rays become weaker inside the CO clumps where the CR electrons cannot penetrate at a sub-pc scale. This suggests that the clumpy ISM may play a crucial role in producing the X-ray
distribution by the shock–cloud interaction, even when the DSA is a fundamental mechanism to create CR electrons.

Aiming at better understanding the results of X- and γ-ray observations and their relationship with the ISM, we are promoting a comprehensive comparison among the γ-rays, the X-rays, and the ISM in γ-ray SNRs (e.g., Fukui 2008, 2013; Paper I; Fukui et al. 2012, hereafter Paper II; Yoshiike et al. 2013). Paper II presented an analysis of the interstellar protons both in molecular and atomic forms and showed a good spatial correspondence between the clumpy ISM protons and the VHE γ-rays. This provides crucial support that the hadronic origin of the γ-rays is dominant instead of the leptonic origin. An alternative idea favoring the leptonic origin of the γ-rays was discussed recently in the context of the hard GeV–TeV γ-ray spectrum, which appears similar to that expected in the leptonic origin (Abdo et al. 2011; see also Ellison et al. 2010, 2012).

It is however argued that the hard spectrum is also explained in the hadronic origin. This is because only higher energy CR protons can interact with the dense gas to produce γ-rays due to energy-dependent penetration of CR protons into the dense gas (Zirakashvili & Aharonian 2010), which produces a spectrum as hard as that observed in RX J1713.7–3946 (Inoue et al. 2012). It should also be noted that the shock–cloud interaction does not favor the leptonic origin, because the interaction amplifies the magnetic field to around 100 μG or even higher, which suppresses significantly the CR electrons via rapid synchrotron cooling and, accordingly, the leptonic component of γ-rays (e.g., Tanaka et al. 2008).

Now, in RX J1713.7–3946, the next step is to establish the connection between the synchrotron X-rays and the inhomogeneous ISM distribution over the entire SNR. The present work is aimed at better understanding the SNR shock–cloud interaction and establishing the origin of the distribution of the synchrotron X-rays in the SNR. This study will be extended to the other SNRs with non-thermal features, allowing us to deepen our understanding on the role of the interacting ISM in the high-energy radiation and in the CR acceleration. In the present paper we show a comparison of the spatial distribution among CO, H1, and X-rays over the whole SNR in order to clarify the relation-ship between dense gas and the high-energy electrons. We will publish a separate paper that deals with a detailed spectral analysis of the Suzaku X-ray results compared with the interstellar gas distribution (H. Sano et al. 2014, in preparation).

The paper is organized as follows. Section 2 gives the description of the data sets of CO, H1, and X-rays and Section 3 gives the analysis. Section 4 gives the discussion and Section 5 the conclusions.

### Table 1

| Pointing ID | ObsID | α2000 (h m s) | δ2000 (° ′ ″) | XIS Exp. (ks) | Date | SCI |
|-------------|-------|---------------|---------------|--------------|------|-----|
| 0........... | 100026010 | 17 12 17.0 | −39 56 11 | 69 | 2005 Sep 26 | OFF |
| 1........... | 501063010 | 17 11 51.5 | −39 31 13 | 18 | 2006 Sep 11 | OFF |
| 2........... | 501064010 | 17 12 38.0 | −39 40 14 | 21 | 2006 Sep 11 | OFF |
| 3........... | 501065010 | 17 12 38.2 | −39 22 15 | 22 | 2006 Sep 11 | OFF |
| 4........... | 501066010 | 17 11 04.5 | −39 40 10 | 21 | 2006 Sep 12 | OFF |
| 5........... | 501067010 | 17 11 05.1 | −39 22 10 | 21 | 2006 Sep 12 | OFF |
| 6........... | 501068010 | 17 14 11.6 | −39 40 14 | 21 | 2006 Sep 13 | OFF |
| 7........... | 501069010 | 17 14 11.4 | −39 22 15 | 18 | 2006 Sep 19 | OFF |
| 8........... | 501070010 | 17 14 11.8 | −39 58 14 | 21 | 2006 Sep 19 | OFF |
| 9........... | 501071010 | 17 12 17.6 | −39 18 50 | 21 | 2006 Sep 20 | OFF |
| 10.......... | 501072010 | 17 15 44.5 | −39 40 10 | 20 | 2006 Oct 5 | OFF |
| 11.......... | 504027010 | 17 11 50.8 | −39 31 00 | 63 | 2010 Feb 15 | ON |
| 12.......... | 504028010 | 17 13 14.0 | −40 14 22 | 19 | 2010 Feb 16 | ON |
| 13.......... | 504029010 | 17 12 39.8 | −40 01 50 | 21 | 2010 Feb 17 | ON |
| 14.......... | 504030010 | 17 15 39.0 | −40 00 47 | 22 | 2010 Feb 17 | ON |
| OFF1........ | 100026020 | 17 09 31.9 | −38 49 24 | 35 | 2005 Sep 25 | OFF |
| OFF2........ | 100026030 | 17 09 05.1 | −41 02 07 | 38 | 2005 Sep 28 | OFF |

**Notes.** The details of pointing ID from 0 to 10, OFF1 and OFF2 are also shown in Takahashi et al. (2008) and Tanaka et al. (2008).
Figure 2. *Suzaku* XIS (XIS 0+1+2+3) mosaic images of RX J1713.7−3946 in the energy bands (a) 1–5 keV and (b) 5–10 keV. The color scale indicates the count rate on a linear scale. The color bar numbers are in units of $10^{-4}$ counts s$^{-1}$ pixel$^{-1}$ with a pixel size of $\sim 16''$. Both images are smoothed with a Gaussian kernel with FWHM of 45''. The positions of the two point-like sources are shown with large circles in (a) (see Table 2). (c) Same XIS mosaic image (1–5 keV) as (a), but the color scale is changed to emphasize the region of low-photon counts below $12 \times 10^{-4}$ counts s$^{-1}$ pixel$^{-1}$. Above this level shown in gray scale, the lowest contour level and the contour interval are 12 and $4 \times 10^{-4}$ counts s$^{-1}$ pixel$^{-1}$, respectively. The small circles, triangles, and squares show the position of seven X-ray point sources, three pulsars, and two Wolf–Rayet stars, respectively.

(A color version of this figure is available in the online journal.)

Table 2

| Name          | $\alpha_{2000}$ ($^\circ$ m s) | $\delta_{2000}$ ($^\circ$) | Source Type             | Ref. |
|---------------|--------------------------------|---------------------------|-------------------------|------|
| WR 84         | 17 11 21.70                    | −39 53 22.2               | Wolf–Rayet star†        | 1    |
| CD−39 11212B  | 17 14 27.129                   | −39 45 47.25              | Wolf–Rayet star         | 2    |
| PSR J1712−3943A | 17 12 35.0                     | −39 43 14                 | pulsar                  | 3    |
| PSR J1712−3943B | 17 12 35.0                     | −39 43 14                 | pulsar                  | 3    |
| PSR J1713−3949 | 17 13 28                      | −39 49.0                 | pulsar†                 | 4    |
| EXMS B1709−397A | 17 12 46                       | −39 48.9                 | X-ray point source      | 5    |
| GPS 1709−396  | 17 12 51.0                     | −39 42 25                 | X-ray point source      | 6    |
| EXMS B1709−397B | 17 13 08                       | −39 48.7                 | X-ray point source      | 5    |
| 1WGA J1713.4−3949 | 17 13 28                  | −39 49.8                 | X-ray point source†     | 4, 7 |
| CXOPS J171340.5−395213 | 17 13 40.5             | −39 52 13                | X-ray point source      | 8    |
| EXO 1710−396  | 17 14 22                       | −39 44.0                 | X-ray point source‡     | 9    |
| 1WGA J1714.4−3945 | 17 14 44                   | −39 45.0                 | X-ray point source‡     | 10, 11 |

Notes. † and ‡ sources are connected with two X-ray point-like sources shown in Figure 2, respectively.

References. (1) van der Hucht 2001; (2) Cutri et al. 2003; (3) Burgay et al. 2006; (4) Lazendic et al. 2003; (5) Reynolds et al. 1999; (6) Gottwald et al. 1995; (7) Landt & Bignall 2008; (8) van den Berg et al. 2012; (9) Lu et al. 1996; (10) Slane et al. 1999; (11) Pfeffermann & Aschenbach 1996.
2. OBSERVATIONS AND DATA REDUCTIONS

2.1. CO

The $^{12}$CO$(J = 2–1)$ data at 230 GHz were taken with the NANTEN2 4 m telescope in the period from August to November in 2008, and were published in Papers I, II, and Maxted et al. (2012). The front end was a 4 K cooled double sideband receiver and a typical system temperature was $\sim 250$ K in the single sideband including the atmosphere toward the zenith. The telescope had an angular resolution (FWHM) of 90$''$ at 230 GHz. We used an acoustic optical spectrometer having 2048 channels with a bandwidth of 390 km s$^{-1}$ and resolution per channel of 0.38 km s$^{-1}$. Observations were carried out in the on-the-fly mode with an integration time of 1.0 s or 2.0 s per grid, and provided a Nyquist-sampled 30$''$ grid data set. The ambient temperature load was employed for the intensity calibration. The absolute intensity scale was estimated by observing the Ori KL object [5h35m14.52; $-5^\circ 22'28.2''$ (J2000)] (Schneider et al. 1998) and the main beam efficiency, $\eta_{mb}$, was estimated to be 0.83. The rms noise fluctuations with 1.0 s and 2.0 s integrations were better than 0.66 K and 0.51 K channel$^{-1}$, respectively. The pointing accuracy was estimated to be better than $\sim 15''$ by...
observing Jupiter every 2 hr. The image was smoothed with a Gaussian kernel with FWHM of 60″.

The velocity resolution and typical rms noise fluctuations were 0.65 km s⁻¹ and 0.3 K, respectively. Observations were carried out in the position-switching mode with a 2′ (A color version of this figure is available in the online journal.)

Figure 5. Distribution of $^{12}$CO J = 2–1) emission (white contours) superposed on the Suzaku 1–5 keV (left) and 5–10 keV (right) images. Velocity range in integration and contour levels are shown in the top of the left and middle panels, respectively. Each arrow indicates the direction of the center of the SNR. The crosses show $^{12}$CO(1-0) data was used for comparison

(A color version of this figure is available in the online journal.)
We used *Suzaku* archive data of RX J1713.7–3946 taken from the Data Archives and Transmission System (DARTS at ISAS/JAXA). The observations performed 15 pointings toward the main features and two OFF pointings of RX J1713.7–3946 and were published by Takahashi et al. (2008) and Tanaka et al. (2008) except for the four pointings observed in 2010 February. Previous and current observations are summarized in Table 1, and the field of view (FoV) of each observation is shown in Figure 1. Active detector systems aboard the *Suzaku* satellite were the X-ray Imaging Spectrometer (XIS; Koyama et al. 2007) and the Hard X-ray Detector (Takahashi et al. 2007). The XIS consists of four CCD cameras placed at the foci of X-Ray Telescopes (XRTs; Serlemitsos et al. 2007). We analyzed only XIS data in the present paper. The spaced-row charge injection (SCI; Nakajima et al. 2008; Uchiyama et al. 2009) was used in the latter four pointings (see also Table 1). Unfortunately, XIS 2 was on closed access since 2006 November 9, possibly owing to micrometeorite damage. XIS 0 showed an anomaly in Segment A on 2009 June 23. Thus, for the data in the latter four pointings we used XIS 0 (except for Segment A), XIS 1, and XIS 3. We used “cleaned event files” processed and screened by versions 2.0 or 2.4 of the *Suzaku* pipeline depending on observation dates. First, we created the photon count images from the cleaned event files in the energy bands 1–5 keV and 5–10 keV. Here, we subtracted the non-X-ray background (NXB) using xisnxbgen, which estimates NXB count rate based on night Earth observation data. Then, we corrected for XRT vignetting effects by simulating flat field images with xissim and 5–10 keV. We performed data reduction with the version 6.11 of the HEAsoft tools.

### 3. Analysis

#### 3.1. Large-scale CO, H\textsubscript{1}, and X-Ray Distributions

Figure 2 shows mosaic images of RX J1713.7–3946, which were constructed by using the data from XIS 0+1+2+3.
Figures 2(a) and (b) show the soft-band (1–5 keV) and hard-band (5–10 keV) images, respectively. The unit for the images is $10^{-4}$ counts s$^{-1}$ pixel$^{-1}$, and the pixel size is $\sim 16^\prime$. We find that the soft- and hard-band images are very similar to each other, which was already discussed in a previous study by Tanaka et al. (2008). Figure 2 shows the western rim clearly as well as several peaks of $\sim 10 \times 10^{-4}$ counts s$^{-1}$ pixel$^{-1}$ in the northern rim and inside the SNR. In the soft-band image, thick white circles indicate the locations of the two bright point-like sources toward the inner part of the SNR. The left one is associated with a Wolf–Rayet star CD−39 11212B (Pfeffermann & Aschenbach 1996), which corresponds to two X-ray point sources cataloged (1WGA J1714.4−3945 and EXO 1710−396; see also Table 2). The other one is thought to be a neutron star because of its X-ray spectral characteristics (Lazendic et al. 2003), which is cataloged as an X-ray point source (1WGA J1713.4−3949) and a pulsar (PSR J1713−3949). We also showed the modified color scale image in the energy band 1–5 keV, which enhances the regions of the low-photon counts $\sim 7 \times 10^{-4}$ counts s$^{-1}$ pixel$^{-1}$. In addition to the localized peaks in X-rays, we find that diffuse X-ray emission is extended inside the SNR. In order to estimate the level of these background X-rays in the 1–5 keV X-ray image, we show two histograms of the X-ray counts in Figure 13 (see Appendix B); one is for the whole region observed with Suzaku (Figure 1) and the other is for the nine circles of 6 arcmin diameter without significant peaks inside the SNR (Figure 13). In the histogram inside the SNR, we find a peak at $\sim 3.86 \times 10^{-4}$ counts s$^{-1}$ pixel$^{-1}$ and identify this level as the background within the SNR. On the other hand, we consider that a primary peak at $\sim 1.16 \times 10^{-4}$ counts s$^{-1}$ pixel$^{-1}$ for the whole region indicates the background level outside the SNR. In Figure 2(c) we plotted the positions of the X-ray point sources, pulsars, and Wolf–Rayet stars (Table 2) in order to test whether the X-ray distribution is influenced by these point sources. We see no excess toward the point sources in Figure 2(c) except for the two bright point-like sources marked in Figure 2(a), and consider that X-ray features inside the SNR are not due to the point sources but are intrinsic to the SNR.

Figure 3 shows four overlays of the $^{12}$CO$(J = 2–1)$ distribution and X-ray images in the two energy bands 1–5 keV.
The CO distribution is highly clumpy. In order to make a detailed comparison with the X-rays, we cataloged CO clumps in the $^{12}$CO($J = 1$–0) data in Figure 12 in Appendix A. We identified 22 CO clumps in total, which were selected by the following two criteria in the $^{12}$CO($J = 1$–0) data; (1) the peak position is located within SNR boundary, (2) the peak brightness temperature is higher than 1 K, and (3) the total clump surface area, defined as the region surrounded by the contour at half of the maximum integrated intensity, is larger than a three-beam area. We give their observed parameters in $^{12}$CO($J = 1$–0) and $^{12}$CO($J = 2$–1) in Table 3. Thirteen of them are identified either by Fukui et al. (2003) or Moriguchi et al. (2005). The rest of the clumps are newly identified in the present work. Most of the clumps have a single velocity component of line width $\sim 3$–5 km s$^{-1}$. Only clump O (Moriguchi et al. 2005) has two velocity components of $\sim 7.5$ km s$^{-1}$ separation, and is divided into two clumps O and O$_b$. Five of them, D$_W$, G$_E$, O$_b$, Q$_W$, and Z, have molecular mass higher than 50 $M_\odot$ (see also Table 3), and four of them, C$_E$, Q$_W$, Z$_W$, and Z$_{NE}$, have molecular mass less than 50 $M_\odot$. We focus hereafter on the 18 CO clumps that have molecular mass greater than 50 $M_\odot$ as shown in Figure 3, so that the derivation of the physical parameters is ensured for a quantitative comparison with the X-rays (Section 2.3). Except for the five clumps, C, I, L, O$_{SW}$, and Z, that are located inside (Figures 3(a) and (b)) and 5–10 keV (Figures 3(c) and (d)), respectively. A $V_{LSR}$ range of CO from $-20.2$ to $-9.1$ km s$^{-1}$ is shown in Figures 3(a) and (c) and that from $-9.1$ to 1.8 km s$^{-1}$ in Figures 3(b) and (d). These velocity ranges correspond to that of the interacting molecular gas (Fukui et al. 2012). Figure 3 indicates that CO and X-rays show a good correlation at a pc scale as already noted by Moriguchi et al. (2005). It is remarkable that most of the X-ray features are found toward CO clumps. The most outstanding X-rays are seen in the west of the shell, where the strongest CO emission is located (Figures 3(b) and (d)). The second brightest X-rays are in the north of the shell, where CO emission is also distributed (Figures 3(a) and (c)). The southern part of the CO emission appears to delineate the southern rim of the SNR (Figures 3(b) and (d)), while the eastern shell with weak X-rays only has a few small CO features (Figures 3(b) and (d)).
the SNR boundary, most of the CO clumps (A, B, D, D_W, E, G, G_E, O, O_b, Q, R, U, and W) are distributed on the outer boundary of the SNR shell.

Finally, we compare the cold H\textsc{i} gas without CO with the X-rays in the southeast-rim of the SNR (hereafter SE-rim; Paper II). The cold H\textsc{i} gas has a density around 100 cm\(^{-3}\) and is likely interacting with the shock in a similar way to CO. Figure 4 shows an enlarged view of the SE-rim overlaid with the H\textsc{i} proton column density contours. The integration range is \(-20.0\) to \(-11.0\) km s\(^{-1}\). We apply the H\textsc{i} self-absorption by following the analysis in Paper II. The lowest contour level and the contour interval in the H\textsc{i} proton column density are \(2.0 \times 10^{21}\) cm\(^{-2}\) and \(0.1 \times 10^{21}\) cm\(^{-2}\), respectively. It is remarkable that the H\textsc{i} distribution corrected for the self-absorption is complementary to the X-ray peaks in the low-photon-count region in the SE-rim.

### 3.2. Detailed Comparison with the X-Rays

In this section we make a detailed comparison of spatial distributions between CO/H\textsc{i} clumps and X-rays in images, radial and azimuthal distributions (Figures 5, 7, and 8).

In the left and middle panels of each row of Figure 5, we show the images of the CO integrated intensity overlaid on the distributions of the soft (1–5 keV, left) and hard (5–10 keV, middle) X-rays. The crosses in each image indicate the center of gravity of the CO clumps listed in Table 4, which is somewhat different from the peak position in Table 3. Each arrow indicates the direction of the center of the SNR. The dashed white circles represent radii 0:06 and 0:12 of the center of gravity. We see a trend that the X-rays are enhanced toward the CO, while the CO peak generally shows offsets from the X-ray peak.

In Figure 5’s right panels, we plot radial profiles of the CO integrated intensity and X-ray counts averaged at each radius for the 1–5 keV and 5–10 keV bands. In order to characterize quantitatively the radial distribution, we first identify the peak in the 1–5 keV radial distribution. In addition, we defined the separation from the center of gravity of the CO clump to the X-ray peak in the radial distribution. Ten of the 17 clumps have peaks of the X-rays and positive X-ray slopes inside the peak in Figure 5. Clump W has no peak but also shows a clear positive X-ray slope. On the other hand, four of the CO clumps show negative slope and the other one shows a nearly flat slope.
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Figure 5. (Continued)

Table 3

Properties of CO Clumps

| Name | \( \alpha_{2000} \) (h m s) | \( \delta_{2000} \) (° ') | \( T_R \) (K) | \( V_{\text{peak}} \) (km s\(^{-1}\)) | \( \Delta V_{\text{LSR}} \) (km s\(^{-1}\)) | Mass \((M_\odot)\) |
|------|-----------------|-----------------|-------------|----------------|----------------|----------------|
| A..... | 17 11 35.9 | -39 59 01.8 | 8.5 | -10.3 | 4.8 | 686 |
| B..... | 17 12 26.5 | -40 06 06.3 | 4.2 | -8.0 | 4.6 | 190 |
| C..... | 17 12 25.9 | -39 56 04.4 | 9.4 | -12.0 | 3.8 | 397 |
| Ck..... | 17 13 01.3 | -39 53 35.2 | 1.1 | -9.1 | 1.6 | 10 |
| D..... | 17 11 28.2 | -39 30 37.6 | 4.0 | -11.1 | 4.8 | 292 |
| Dw..... | 17 11 01.3 | -39 34 17.6 | 2.5 | 2.4 | 3.3 | 137 |
| E..... | 17 11 29.1 | -39 50 38.5 | 2.0 | -6.1 | 7.2 | 159 |
| G..... | 17 10 55.6 | -39 45 55.2 | 3.3 | -10.8 | 8.0 | 307 |
| Gk..... | 17 11 27.1 | -39 47 49.6 | 5.4 | -12.8 | 2.6 | 168 |
| L..... | 17 12 08.2 | -39 43 43.3 | 1.8 | -9.9 | 5.4 | 103 |
| Lw..... | 17 12 25.8 | -39 28 53.4 | 4.0 | -12.0 | 5.7 | 370 |
| O..... | 17 13 46.7 | -39 27 49.8 | 1.1 | -6.4 | 4.9 | 61 |
| Ov..... | 17 13 46.7 | -39 27 49.8 | 1.1 | -6.4 | 4.9 | 61 |
| Osv..... | 17 13 24.8 | -39 37 08.6 | 2.8 | -1.6 | 2.0 | 60 |
| Q..... | 17 15 23.4 | -39 25 06.2 | 2.9 | -2.8 | 3.2 | 108 |
| Qw..... | 17 15 49.3 | -39 31 35.1 | 3.0 | -14.3 | 2.4 | 46 |
| R..... | 17 15 39.9 | -39 38 34.6 | 4.1 | -3.3 | 2.4 | 67 |
| U..... | 17 14 34.2 | -40 06 27.0 | 3.7 | -4.8 | 1.3 | 58 |
| W..... | 17 14 22.8 | -40 16 40.7 | 5.0 | -5.1 | 3.0 | 402 |
| Z..... | 17 14 18.7 | -39 56 55.1 | 2.6 | -20.1 | 2.7 | 72 |
| Zh..... | 17 13 45.0 | -39 52 14.9 | 3.0 | -19.8 | 2.6 | 36 |
| NZ..... | 17 14 57.4 | -39 49 59.3 | 2.2 | -20.0 | 3.3 | 31 |

\( ^{12}\text{CO}(J = 1\rightarrow 0) \)

| \( \alpha_{2000} \) (h m s) | \( \delta_{2000} \) (° ') | \( T_R \) (K) | \( V_{\text{peak}} \) (km s\(^{-1}\)) | \( \Delta V_{\text{LSR}} \) (km s\(^{-1}\)) |
|-----------------|-----------------|-------------|----------------|----------------|
| A..... | 17 11 38.4 | -39 58 46.9 | 6.6 | -10.0 | 4.5 |
| B..... | 17 12 26.8 | -40 05 55.5 | 3.3 | -8.1 | 4.5 |
| C..... | 17 12 27.0 | -39 54 58.0 | 7.5 | -11.9 | 4.6 |
| Ck..... | 17 12 57.4 | -39 53 42.3 | 3.7 | -8.8 | 4.1 |
| D..... | 17 11 32.5 | -39 30 03.9 | 3.3 | -9.3 | 4.8 |
| Dw..... | 17 11 34.3 | -39 32 31.2 | 3.1 | -1.1 | 6.0 |
| E..... | 17 11 55.4 | -39 51 07.2 | 2.0 | -6.0 | 5.0 |
| G..... | 17 10 56.3 | -39 45 20.6 | 2.8 | -11.5 | 4.8 |
| Gk..... | 17 11 21.0 | -39 47 24.4 | 4.3 | -12.3 | 2.7 |
| L..... | 17 12 16.6 | -39 43 22.8 | 1.3 | -10.4 | 5.9 |
| Lw..... | 17 12 30.2 | -39 28 14.6 | 3.2 | -11.7 | 6.0 |
| O..... | 17 13 46.0 | -39 26 28.6 | 1.2 | -4.6 | 4.7 |
| Ov..... | 17 13 46.0 | -39 26 28.6 | 1.2 | -4.6 | 4.7 |
| Q..... | 17 15 11.7 | -39 26 47.4 | 2.8 | -2.2 | 2.8 |
| Qw..... | 17 15 11.7 | -39 26 47.4 | 2.8 | -2.2 | 2.8 |
| R..... | 17 14 53.0 | -39 31 30.7 | 3.7 | -14.1 | 1.8 |
| U..... | 17 15 32.0 | -39 39 28.5 | 3.2 | -3.1 | 2.2 |
| W..... | 17 14 34.3 | -40 06 25.2 | 3.0 | -4.6 | 1.3 |
| Z..... | 17 13 30.0 | -40 15 03.6 | 3.3 | -4.9 | 3.4 |
| Zh..... | 17 13 53.3 | -39 54 46.8 | 2.9 | -19.8 | 2.9 |
| NZ..... | 17 13 53.3 | -39 49 25.7 | 3.6 | -19.6 | 2.5 |

Notes. Column 1: clump name. Columns 2–7 and 8–12: observed properties of the \(^{12}\text{CO}(J = 1\rightarrow 0, 2\rightarrow 1)\) spectra obtained at the peak positions of the CO clumps. Columns 2–3: position of the peak CO intensity. Column 4: peak radiation temperature \(T_R\). Column 5: \(V_{\text{peak}}\) derived from a single Gaussian fitting. Column 6: FWHM line width \(\Delta V_{\text{LSR}}\). Column 7: total mass of the clumps derived by using the relation between the molecular hydrogen column density \(N(\text{H}_2)\) and the \(^{12}\text{CO}(J = 1\rightarrow 0)\) intensity \(W(12\text{CO})\), \(N(\text{H}_2) = 2.0 \times 10^{20}[W(12\text{CO}) \text{ (K km s}^{-1}) \text{ cm}^{-2}]\) (Bertsch et al. 1993). See also the text for more details. Columns 8–12: the observed properties shown with Columns 2–6 for the \(^{12}\text{CO}(J = 2\rightarrow 1)\) spectra. The properties of A–C, D, E, G, I–O, Q, and R–W derived from \(^{12}\text{CO}(J = 1\rightarrow 0)\) are shown by Moriguchi et al. (2005) and Sano et al. (2010).
The radial distributions of the X-rays are generally smooth and monotonic so that linear approximation is reasonable in estimating the intensity gradients. Only the CO clumps O+O\textsubscript{b} show a complicated non-monotonic radial distribution of the X-rays, which may be due to the blending of the two velocity components. We made least-squares fit to the X-rays by a straight line for simplicity for the 10 clumps within the peak, and for clump W and the other six clumps within a radius of 0.06. The values of the slope are listed in Table 5, and are shown as a histogram in Figure 6. Twelve of the 16 clumps (75\%) show positive slopes in the X-rays, indicating that the X-rays show a decrease toward the CO clump and are brightened in the surroundings of the CO clump. For the remaining four with negative or flat slopes, except for clump Z, we also find clear relative enhancement of the X-rays in the surroundings of the CO clumps (Figure 5, left and middle panels). Clump Z has no clear X-ray depression toward the center, while enhanced X-rays are seen in its surroundings (Figure 5, left and middle panels in the last low). We conclude that the enhanced X-rays around the CO clumps are a general trend among the CO clumps, as is consistent with the previous result on clump C (Paper I). We note that the averaged behavior is that the CO clumps have a radius of 0.04 ± 0.01 and the X-rays are distributed with a separation 0.07 ± 0.03 from the center of each clump (see also Table 4).

In addition, we made a similar analysis on the cold H\textsubscript{i} in the SE-rim. The H\textsubscript{i} distribution estimated from self-absorption well delineates the outer boundary of the X-rays (Figure 7), and their relative distributions are similar to the case of clump A. The H\textsubscript{i} column density distribution is fairly flat with no clear peak. Instead of using the H\textsubscript{i} peak, we draw a line passing through the center of the SNR and the soft X-ray peak, and define the H\textsubscript{i} column density peak on this line. The radial distributions are plotted centered on this H\textsubscript{i} peak. We find that the X-rays are clearly enhanced around the cold H\textsubscript{i}, which is a trend similar to the CO clumps.

The top three panels of Figure 8 show the same XIS mosaic images (1–5 keV) as in Figure 2(c). The lines connecting the CO/H\textsubscript{i} clump positions (shown in Figures 5, 7, and Table 4) and the center of the SNR (l, b) = (347.3, −0.5) or (θ\textsubscript{2000}, δ\textsubscript{2000}) = (17°13′34″, −39°48′17″) are taken as the origins of

| Name | α\textsubscript{2000} (h m \textsuperscript{−1}) | δ\textsubscript{2000} (°) | V\textsubscript{LSR} (km s\textsuperscript{−1}) | Radius (deg) | Separation (deg) | Peak Intensity (×10\textsuperscript{−4} counts s\textsuperscript{−1} pixel\textsuperscript{−1}) | Angle (Fraction) (deg, %) | Interacting Mass (M\textsubscript{\odot}) |
|------|----------------|----------------|----------------|---------------|----------------|---------------------------------|-----------------|-----------------|
| A... | 17 11 39.1     | −39 59 22.2    | −14.5 to −5.7  | 0.050         | 0.065         | 18.50 ± 0.07                | −120 to +120, (67) | 460 ± 60        |
| B... | 17 12 25.3     | −40 05 37.5    | −12.7 to −3.6  | 0.050         | 0.025         | 10.88 ± 0.05                | −150 to +90, (67) | 130 ± 20        |
| C... | 17 12 25.3     | −39 55 07.4    | −16.6 to −7.4  | 0.040         | 0.035         | 19.64 ± 0.07                | −180 to +180, (100) | 400 ± 30        |
| D... | 17 11 31.9     | −39 29 13.6    | −14.2 to −4.6  | 0.040         | ...           | 22.25 ± 0.07                | −150 to +150, (83) | 240 ± 20        |
| E... | 17 11 12.8     | −39 32 43.5    | −7.2 to 4.8    | ...           | ...           | 21.18 ± 0.07                | −120 to +90, (58) | 80 ± 11         |
| G... | 17 11 38.7     | −39 50 56.8    | −8.1 to −4.0   | ...           | ...           | 19.81 ± 0.07                | −180 to +180, (100) | 159 ± 13        |
| L... | 17 10 54.5     | −39 46 25.7    | −16.4 to −6.8  | 0.050         | 0.075         | 11.81 ± 0.09                | −60 to +60, (33)  | 100 ± 30        |
| O... | 17 11 22.2     | −39 37 34.0    | −15.1 to −9.8  | 0.050         | 0.025         | 13.16 ± 0.13                | −150 to +150, (83) | 140 ± 14        |
| O\textsubscript{b} | 17 12 09.3     | −39 43 11.9    | −16.4 to −4.6  | 0.030         | 0.075         | 14.22 ± 0.07                | −180 to +180, (100) | 103 ± 9         |
| O\textsubscript{SW} | 17 12 28.2     | −39 28 45.9    | −17.7 to −5.7  | 0.045         | 0.105         | 19.91 ± 0.07                | −180 ± 180, (100) | 370 ± 30        |
| O+O\textsubscript{b} | 17 13 48.9     | −39 26 24.9    | −11.3 to −1.6  | 0.055         | 0.095         | 14.02 ± 0.14                | −120 to +120, (67) | 41 ± 5          |
| O\textsubscript{b} | 17 13 46.9     | −39 26 45.9    | −4.6 to 2.2    | 0.035         | 0.085         | 13.92 ± 0.14                | −120 to +120, (67) | 53 ± 7          |
| D+DW | ...           | ...           | ...           | 0.080         | 0.212         | 21.72 ± 0.05                | ...             | 320 ± 30        |
| O+O\textsubscript{b}+O\textsubscript{SW} | ...       | ...           | ...           | 0.149         | 0.099         | 14.19 ± 0.09                | ...             | 154 ± 10        |
| G+Gr | ...           | ...           | ...           | 0.129         | 0.088         | 12.49 ± 0.08                | ...             | 240 ± 30        |
| E+H\textsubscript{i} | ...       | ...           | ...           | 0.172         | 0.055         | 17.02 ± 0.05                | ...             | 260 ± 20        |
the azimuth angle, which is measured counterclockwise. The azimuthal angular distribution of the X-rays around each CO/H\textsubscript{i} clump is estimated with respect to the direction of the center of the SNR. We measured the azimuthal angular extent of the X-rays passing through the X-ray peak in the 1–5 keV image. The crosses show the position that represents the cold H\textsubscript{i} clump and is determined as the crossing point of the H\textsubscript{i} cloud with the arrow. (\(\rho_{12000}, \phi_{12000}\)) = (17\textsuperscript{h}16\textsuperscript{m}9\textsuperscript{s}, -40\degree\,31\arcmin\,6) (see also the text). The dashed white circles represent radii of 0\degree\,06 and 0\degree\,12 centered on the crosses. The right panel shows the radial profile along the crosses in H\textsubscript{i} column density and the X-ray counts in the two energy bands (1–5 keV and 5–10 keV in Figure 2). The radial profile in the 5–10 keV band is scaled by a factor of eight of the 1–5 keV band for the sake of direct comparison. The orange dash–dotted line indicates X-ray peak radius in the 1–5 keV band.

Figure 7. Distribution of the cold H\textsubscript{i} column density (white contours) superposed on the Suzaku images in the 1–5 keV (right) and 5–10 keV (middle) bands. Velocity range of integration and contour levels are shown in the top of the left and middle panels, respectively. Each arrow indicates the direction of the center of the SNR passing through the X-ray peak in the 1–5 keV image. The crosses show the position that represents the cold H\textsubscript{i} clump and is determined as the crossing point of the H\textsubscript{i} cloud with the arrow. (\(\rho_{12000}, \phi_{12000}\)) = (17\textsuperscript{h}16\textsuperscript{m}9\textsuperscript{s}, -40\degree\,31\arcmin\,6) (see also the text). The dashed white circles represent radii of 0\degree\,06 and 0\degree\,12 centered on the crosses. The right panel shows the radial profile along the crosses in H\textsubscript{i} column density and the X-ray counts in the two energy bands (1–5 keV and 5–10 keV in Figure 2). The radial profile in the 5–10 keV band is scaled by a factor of eight of the 1–5 keV band for the sake of direct comparison. The orange dash–dotted line indicates X-ray peak radius in the 1–5 keV band.

(A color version of this figure is available in the online journal.)

The azimuthal angular distribution of the X-rays around each CO/H\textsubscript{i} clump is estimated with respect to the direction of the center of the SNR. We measured the azimuthal angular extent of the X-rays in each clump in the 1–5 keV band image by adopting the background level inside the SNR as the threshold (Section 3.1). The results are shown in Figure 8 and Table 4. Figure 9’s upper panel shows the range of angles and the lower panel shows a histogram of the peak angle. The five clumps inside the SNR, clumps C, E, I, L, and O\textsubscript{SW}, are fully surrounded by the X-rays, which show a peak toward the azimuthal angle \(-180\degree\) to \(-120\degree\) (clumps C, I, and O\textsubscript{SW}) or \(+60\degree\) to \(+120\degree\) (clumps E and L). These distributions indicate that the clumps inside the SNR are surrounded by the enhanced X-rays, whereas those on the border of the SNR have enhanced X-rays only toward the center of the SNR. In Figure 9’s lower panel we see a trend that the X-rays are enhanced at an azimuthal angle around 0, while scattering is large, \pm\,60\degree\ (clumps A, D, D\textsubscript{W}, G, G\textsubscript{E}, O\textsubscript{+Ob}, Q, R, U, W, Z, and SE-rim). The histogram was fitted by a Gaussian function from \(-120\degree\) to \(120\degree\), and we find that the best-fit parameters of center and sigma are \(14\degree\,\pm\,5\degree\) and \(51\degree\,\pm\,5\degree\), respectively.

Table 5

| Name     | Fitting Range (deg) | Slope \(\times 10^{-4}\) counts s\(^{-1}\) pixel\(^{-1}\) | Comments                |
|----------|---------------------|--------------------------------------------------------|-------------------------|
| A        | 0.00–0.07           | +152 ± 2                                               | Positive slope with peak |
| B        | 0.00–0.03           | +40 ± 10                                              | Positive slope with peak |
| C        | 0.00–0.04           | +56 ± 6                                               | Positive slope with peak |
| D        | 0.00–0.06           | −59 ± 2                                               | Negative slope          |
| D\textsubscript{W} | 0.00–0.06        | −84 ± 3                                               | Negative slope          |
| E        | 0.00–0.11           | +82 ± 1                                               | Positive slope with peak |
| G        | 0.00–0.08           | +57 ± 1                                               | Positive slope with peak |
| G\textsubscript{E} | 0.00–0.03       | +40 ± 20                                              | Positive slope with peak |
| I        | 0.00–0.08           | +70 ± 2                                               | Positive slope with peak |
| L        | 0.00–0.10           | +2 ± 1                                                | Flat                    |
| O\textsubscript{+Ob} | …                   | …                                                      | …                       |
| Q        | 0.00–0.09           | +43 ± 3                                               | Positive slope with peak |
| R        | 0.00–0.03           | +20 ± 20                                              | Positive slope with peak |
| U        | 0.00–0.10           | −10 ± 10                                              | Negative slope          |
| W        | 0.00–0.06           | +10 ± 2                                               | Positive slope with no peak |
| Z        | 0.00–0.06           | −79 ± 4                                               | Negative slope          |

Notes. Column 1: clump name. Column 2: fitting range of X-rays in radial plot (see also the text for details). Column 3: slope of the fitted straight line of X-rays with 1\sigma error in the least-squares fitting. Column 4: comments.
Figure 8. Top panels: same XIS mosaic image (1–5 keV) as Figure 2(c). Overlaid white circles are centered on the center of gravity of each CO/H\textsc{i} clump. The azimuthal distribution of X-rays is averaged within each circle (radius = 0.12). Each white solid straight line connects the centers of the circle and the SNR, and each dashed white line in the circle is vertical to the solid line. The azimuthal angle is measured from the solid line as the origin counterclockwise from \(-180^\circ\) to \(180^\circ\) (e.g., clump Q in top panel). Other panels: azimuthal distributions of Suzaku XIS 1–5 keV (red square) and 5–10 keV (green triangles are scaled by a factor of eight) averaged in the circles for each clump. The horizontal solid lines indicate the background level of the X-rays estimated inside the SNR for the energy band 1–5 keV (see the text).

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X-rays is proportional to the \((-8/3)\)th power of the energy and is expressed as follows (Longair 1994);

\[
\tau_x = 2 \times 10^{-22} \, N_\text{H} \, (\text{cm}^{-2}) \cdot \varepsilon^{-8/3} \, (\text{keV}),
\]

where \(N_\text{H} \, (\text{cm}^{-2})\) is the ISM column density and \(\varepsilon \, (\text{keV})\) is X-ray photon energy. The maximum ISM column density in the SNR is estimated to be \(1 \times 10^{22} \, \text{cm}^{-2}\) toward the brightest CO peak, peak C (e.g., Sano et al. 2010). Even for this column density absorption optical depths are 2, 0.3, 0.03, and 0.004 at 1 keV, 2 keV, 5 keV, and 10 keV, respectively, as calculated by Equation (1), and absorption does not likely affect the X-ray distribution significantly. We made a test on the X-ray absorption toward clump C, where the X-rays show depression, which may be due to absorption. The X-ray intensity ratio toward clump C is \(\sim 8.6\) between the 1–5 keV and 5–10 keV bands as observed by Suzaku (H. Sano et al. 2014, in preparation). By using Xspec we calculated the X-ray intensity integrated over the two energy bands for three different values of absorbing column density (i.e., 0.3, 1, and \(3 \times 10^{22} \, \text{cm}^{-2}\)) for an X-ray photon index of 2.3, and found that the intensity ratios between the two bands are \(\sim 11.1, 7.0, \) and 3.5, respectively. Column density slightly less than \(1 \times 10^{22} \, \text{cm}^{-2}\) fits the X-ray observations reasonably well as is consistent with the CO observations.

4. DISCUSSION

Paper I showed that the synchrotron X-ray emission is enhanced around the CO clumps in the northwest region of RX J1713.7–3946. In the present paper, we have compared the X-rays and the CO and H\textsc{i} dense clumps over the whole SNR, and present a schematic image of these results in Figure 10.

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This figure indicates that the CO and dense H\textsc{i} clumps form an inhomogeneous shell and that the X-rays are enhanced around all the clumps. We infer that the five CO clumps C, E, I, L, and OSW survived the SNR blast waves and are embedded within the SNR, while the other twelve CO clumps and the H\textsc{i} clump are shock-interacting on their inner side. The ISM shell was formed over a timescale of Myr by the stellar winds of an O-type star (Weaver et al. 1977), the gas density inside the evacuated wind bubble is \(~\sim\)0.01 cm\(^{-3}\), which applies to the interior of the cavity. The shock waves of the SNR first propagated in the stellar-wind cavity and then began interacting with the CO/H\textsc{i} clumps some 1000 yr ago, as given by the ratio of the shell thickness and the shock velocity, 3 pc/3000 km s\(^{-1}\). According to MHD numerical simulations by Inoue et al. (2012), the CO/H\textsc{i} clumps having a density of \(~\sim\)10\(^{2}\)–10\(^{3}\) cm\(^{-3}\) are surrounded by the interclump gas with a density of \(~\sim\)1 cm\(^{-3}\), which is two orders of magnitude higher than that in the cavity. These authors show that the shock is stalled in the dense clumps. The shock velocity becomes \(V_{\text{sh,clump}} = V_{\text{sh,interclump}}\sqrt{n_{\text{interclump}}/n_{\text{clump}}}\), where the interclump density \(n_{\text{interclump}} = 1\) cm\(^{-3}\) and the clump density \(n_{\text{clump}} = 10^{2}–10^{3}\) cm\(^{-3}\). The shock velocity difference between the dense CO/H\textsc{i} clumps and the interclump gas will become a factor of \(~\sim\)10–30. They calculated that the temperature of the shocked dense gas becomes much lower than the temperature in the post-shock diffuse gas, and argued that the thermal X-ray emission from the CO/H\textsc{i} clumps is strongly suppressed after the passage of the shock (see Section 4.3 of Inoue et al. 2012). The interclump gas does not emit significant thermal X-rays either, because the density \(~\sim\)1 cm\(^{-3}\) is less than \(~\sim\)2 cm\(^{-3}\), the average density inside the SNR obtained from the upper limit of the thermal X-rays (Takahashi et al. 2008).

An important consequence of the interaction is that the large velocity difference created between the clumps and the interclump space induces turbulence, which leads to turbulent dynamo action. The magnetic field is then amplified to as high as 1 mG, which is consistent with the field strength derived from the rapid time variation of the X-ray filaments (Uchiyama et al. 2007), while an alternative is that the fluctuations in the field orientation may explain the rapid time variation (Helder et al. 2012). The synchrotron flux integrated in the line of sight is proportional to \(B^{1.5}\) if the spectral index of electron \(\rho = 2.0\) (Rybicki & Lightman 1979). So, it is possible to enhance the X-ray radiation around the CO and H\textsc{i} clumps. It is known that the power of the synchrotron X-ray emission is not enhanced by magnetic field amplification due to the effect of synchrotron cooling, if the amplification takes place in the vicinity of the forward shock where electrons are being accelerated (e.g., Nakamura et al. 2012). In the present case, as discussed by Inoue et al. (2009, 2010, 2012), the magnetic field amplification owing to the shock–cloud interaction is effective at least 0.1 pc downstream of the shock front. This indicates that the synchrotron X-rays are emitted after the acceleration process, and thus the power of the synchrotron X-ray is enhanced by the amplification. The observed power of the X-ray emission around the CO and H\textsc{i} clumps is 2 to 7 times higher than the background level inside the SNR. Then, the magnetic field around the CO and H\textsc{i} clumps is estimated to be 2 to 4 times higher than elsewhere in the SNR, if the X-ray enhancement is only due to the magnetic field amplification. The averaged magnetic field around the CO and H\textsc{i} clumps becomes 30–60 \(\mu\)G if the initial field is assumed to be 15 \(\mu\)G (Tanaka et al. 2008). The average field strength is also estimated by the width of synchrotron X-ray filaments as \(~\sim\)100 \(\mu\)G (Bell 2004; Hiraga et al. 2005; Ballet 2006). Note that the dependence of the synchrotron flux on the magnetic field strength can be much more sensitive than the above-mentioned standard case, because the high-energy electrons that contribute the X-ray synchrotron emission can be in the cut-off regime (Bykov et al. 2008). Moreover, such enhanced magnetic field in turbulence may lead to more efficient acceleration than in the DSA (Lazarian & Vishniac 1999; Hoshino 2012).

Finally, we discuss the quantitative relationship between the CO/H\textsc{i} interacting clump mass and the X-ray enhancement. First, we estimate the interacting clump mass (Column 9 of...
Figure 10. Schematic image of the distribution of the molecular (CO) clumps (open crosses), atomic (H\(_i\)) clump (circle), and the X-rays (shaded partial or full circles) superposed on the Suzaku 1–5 keV X-ray outer boundary of the SNR (gray contours). The black open crosses (clumps C, I, E, L, and O\(_{SW}\)) indicate those fully surrounded by the X-rays.

Table 4) with the shock waves as defined by the total CO/H\(_i\) mass within the azimuth angle range of the X-rays with respect to the center of gravity (Column 8 of Table 4). For the case in which two CO clumps have small separation (<0.2) and the X-ray peak is situated between the CO clumps, we sum up the interacting clump masses and average the X-ray intensities (D+D\(_W\), O+O\(_{SW}\)+O\(_{SW}\), G+G\(_E\), and E+I; see also Table 4). In

Figure 11, we plot the CO/H\(_i\) interacting clump mass as a function the X-ray peak intensity. Here, we approximate the mass of the SE-rim to be 134 M\(_\odot\) on the assumption that it has an area of 0.8 pc\(^2\) along the X-ray boundary. The result, shown in Figure 11, indicates that the correlation between the interacting clump mass and the X-ray intensity is good with a correlation coefficient of \(\sim 0.85\) in double logarithm. We conclude that intensity is roughly proportional to the interacting mass of each CO/H\(_i\) clump at a pc scale. This result suggests that the ISM distribution is crucial in producing the non-thermal X-ray distribution in young SNRs.

5. CONCLUSIONS

We summarize the present work as follows.

1. We have shown that all the major CO and H\(_i\) clumps with mass greater than 50 M\(_\odot\) interacting with the shock waves in RX J1713.7–3946 are associated with the non-thermal X-rays. The X-rays are enhanced within \(\sim 1\) pc of the CO and H\(_i\) peaks, whereas at smaller scales down to 0.1 pc the CO peaks tend to be anti-correlated with the X-rays, which are decreased toward the CO and H\(_i\) clumps. We have shown a good correlation between the CO/H\(_i\) clump mass interacting with the shock waves and the X-ray intensity.

2. The present findings in (1) are compared with numerical simulations of MHD in a realistic highly inhomogeneous density distribution by Inoue et al. (2009, 2012). These simulations indicate that the magnetic field is amplified around dense CO/H\(_i\) clumps as a result of enhanced turbulence induced by the shock–cloud interaction. We interpret that thus-amplified magnetic fields enhance the X-ray intensity, which depends on the 1.5th power of the magnetic field strength. Such an enhanced magnetic field may also lead to efficient acceleration additional to the DSA. More comparative studies of the distribution of...
Figure 12. Velocity channel distributions of the $^{12}$CO($J = 1-0$) (top panels in false color) and $^{12}$CO($J = 2-1$) (bottom panels in false color) emissions overlaid on the Suzaku X-ray contours for the energy band 1–5 keV. Each panel of CO shows intensity distributions integrated every 2 km s$^{-1}$ in a velocity range from $-24$ to 8 km s$^{-1}$ following the color code shown on the upper right. In the X-ray distribution, the lowest contour level and the contour interval are 2.1 and $0.6 \times 10^{-4}$ counts s$^{-1}$ pixel$^{-1}$, respectively. The CO clumps shown in Table 3 are also plotted.

(A color version of this figure is available in the online journal.)

the X-rays and the ISM will allow us to have a deeper insight into the origin of the X-ray distribution.

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APPENDIX A

VELOCITY CHANNEL DISTRIBUTIONS OF THE CO CLUMPS

In order to clarify a relationship between X-rays and CO clumps, it is necessary to identify all the CO clumps interacting...
with the SNR blast waves. The previous studies (e.g., Fukui et al. 2003; Moriguchi et al. 2005; Sano et al. 2010) identified most of the CO clumps, but it was not complete because the velocity range was limited (e.g., \( V_{LSR} < -12 \text{ to } -3 \text{ km s}^{-1} \) in Moriguchi et al. 2005). We therefore identified all the CO clumps interacting with the SNR blast waves for a wide velocity range, such as in Fukui et al. (2012). \( V_{LSR} \) from 2 km s\(^{-1}\) to 2 km s\(^{-1}\). We used the velocity channel maps and appropriate criteria to identify other CO clumps (see also Section 3.1).

Figure 12 shows the velocity channel distribution of \(^{12}\)CO (J = 1–0, 2–1) every 2 km s\(^{-1}\) from -24 km s\(^{-1}\) to 8 km s\(^{-1}\) superposed on the Suzaku X-ray distribution (1–5 keV). We also plotted the position of each CO clump interacting with the SNR. The clumps, CE, DW, G_E, O_h, O_SW, Q_W, Z, Z_NW, and Z_NE, are newly identified in present work.

**APPENDIX B**

**THE BACKGROUND LEVEL OF X-RAYS**

In order to estimate the azimuth distribution of the X-rays in Figure 8, we estimated the background level of the X-rays in the energy band 1–5 keV inside the SNR. Figure 13 shows two histograms of the X-rays. One is extracted from the whole region as shown in Figure 1, and the other is the inner typical part of the SNR. The latter is extracted from nine circles of 6 arcmin \((\text{circle} \times 9)\) that enclose the typical inner region of the SNR, respectively. (b) Same XIS mosaic image (1–5 keV) as Figure 2(c). The region enclosed by the broken solid lines and that enclosed by the nine circles represents the whole and typical inner region used for (a), respectively.

(A color version of this figure is available in the online journal.)

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