X-ray spectroscopy of the mixed morphology supernova remnant W 28 with XMM-Newton

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Abstract

We report on spatially resolved X-ray spectroscopy of the north-eastern part of the mixed morphology supernova remnant (SNR) W 28 with XMM-Newton. The observed field of view includes a prominent and twisted shell emission forming the edge of this SNR as well as part of the center-filled X-ray emission brightening toward the south-west edge of the field of view. The shell region spectra are in general represented by an optically thin thermal plasma emission in collisional ionization equilibrium with a temperature of $\sim 0.3$ keV and a density of $\sim 10$ cm$^{-3}$, which is much higher than the density obtained for inner parts. In contrast, we detected no significant X-ray flux from one of the TeV $\gamma$-ray peaks with an upper-limit flux of $2.1 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ in the 2–10 keV band. The large flux ratio of TeV to X-ray, larger than 16, and the spatial coincidence of the molecular cloud and the TeV $\gamma$-ray emission site indicate that the TeV $\gamma$-ray of W 28 is $\pi^0$-decay emission originating from collisions between accelerated protons and molecular cloud protons. Comparing the spectrum in the TeV band and the X-ray upper limit, we obtained a weak upper limit on the magnetic field strength $B \lesssim 1500$ $\mu$G.

Key words: acceleration of particles — ISM: individual objects (W 28) — ISM: supernova remnants — X-rays: ISM

1 Introduction

Supernova remnants (SNRs) are one of the most promising acceleration sites of cosmic rays up to $\sim 10^{15.5}$ eV (the knee energy). Koyama et al. (1995) discovered synchrotron X-rays from the shell of SN 1006, indicating the existence of extremely high-energy electrons up to $\sim$ TeV produced by the first-order Fermi acceleration. Following this discovery, the synchrotron X-ray emission has been discovered from a few more young shell-type SNRs, such as RX J1713.7–3946 (Koyama et al. 1997), RCW 86
timescales in the north-east and central regions imply that the gas is close to the ionization equilibrium. Recently, Suzaku discovered that the thermal X-ray emission from the inner region is over-ionized, implying that the plasma may have undergone sudden rarefaction (Sawada & Koyama 2012). These facts imply that W28 is an ideal target to study the particle escape from the shock.

We analyzed XMM-Newton archival data of the north-eastern part of W28, where the molecular clouds, OH maser spots, bright X-ray shells, GeV, and TeV emission were detected. XMM-Newton has a large effective area and high angular resolution. These characteristics enable us to carry out high quality spatially resolved spectroscopy. In section 2, we present the observation log and data reduction method. Imaging and spectral analyses are shown in sections 3 and 4, respectively. From one of the TeV γ-ray emission regions, we only obtained an upper limit on the X-ray flux. Discussions are made on the basis of these results in section 5 on the nature of the thermal and non-thermal components in multi-wavelength. Finally, we summarize our results in section 6.

2 Observation and data reduction

The north-eastern part of W28 was observed with the European Photon Imaging Camera (EPIC) on board the XMM-Newton Observatory on 2002 September 23 (ObsID = 0145970101) and 2003 October 7 (ObsID = 0145970401). The nominal pointing position was $\alpha = -270^\circ:438$, $\delta = -23^\circ:300$ (J2000.0). All of the EPIC instruments were operated in the full-frame mode with a thick filter. We used version 7.0.0 of the Standard Analysis System (SAS) software, and selected X-ray event with PATTERN keywords of $\leq 12$ for the MOS1/2 and $\leq 4$ for the pn, respectively.

The net exposure times were 54.1 ks and 49.9 ks for the MOS1/2 and the pn, respectively, after combining the 2002 and 2003 data. To remove the high particle background time intervals, we accumulated a lightcurve in the 10–12 keV band from the whole field of view, and filtered the time intervals when the count rate was larger than 0.35 counts s$^{-1}$ for the MOS and 0.4 counts s$^{-1}$ for the pn. After this screening, the effective exposure time of MOS1, MOS2, and pn were 51.9 ks, 52.1 ks, and 39.6 ks, respectively.

3 Image analysis

Figure 1 shows the exposure-corrected MOS images in 0.3–2.0 keV and 2.0–10.0 keV with a binning size of 25′′:6. They were created by combining all the MOS1/2 data from the 2002 and 2003 observations. In the low-energy band (figure 1a), the shell region located at $(l, b) \approx (6:70, -0:26)$
is the brightest. Its shape is twisted in a complex manner. The inner region of W 28, toward the south-west of the image, is also enhanced in surface brightness. In the high-energy band (figure 1b), on the other hand, the shell region is much fainter than the inner region.

Figure 2 shows intensity contours of CO \((J = 3–2)\) and CO \((J = 1–0)\) in red and blue (Arikawa et al. 1999) and those of TeV \(\gamma\)-ray measured with H.E.S.S. in yellow (Aharonian et al. 2008), overlaid on the 0.3–2.0 keV gray scale MOS image (figure 1a). The CO \((J = 3–2)\) and \((1–0)\) contours trace distributions of post-shock and pre-shock molecular clouds, respectively (Arikawa et al. 1999). The green dots represent OH maser spots, which also indicate the presence of shock waves (Claussen et al. 1997). GeV emission is from the same region as TeV emission (Abdo et al. 2010c; Giuliani et al. 2010). The eastern bunch of the OH maser sources spatially coincides with the edge of the X-ray bright shell, as well as the edge of the eastern molecular cloud. This indicates that the shock is formed there. The edge of one of the TeV \(\gamma\)-ray peaks seems to appear at the same position. OH maser spots are also detected with spatial coincidence with a molecular cloud region which extends linearly from the X-ray shell toward the western edge of the image. In the southern part of the image, the molecular clouds coincide with the other TeV \(\gamma\)-ray emission peak, where the surface brightness of the X-ray emission is somewhat reduced. From this region, several OH maser spots are also detected. They are all within the error circle of the GeV \(\gamma\)-ray source.
4 Spectral analysis

In this section, we present the results of spatially resolved spectral analysis. We concentrate our analysis on the shell regions and the eastern peak of the TeV γ-ray emission, since the inner region has been studied with good statistics from Suzaku (Sawada & Koyama 2012). In evaluating the spectra, we utilized XSPEC (version 11.3.2) in the band 0.3–10.0 keV. We created ancillary response files (ARF) by assuming flat brightness distribution within each source integration region. As emission spectral models, we basically adopt the NEI model to represent optically thin thermal spectra in ionization non-equilibrium. In some cases where the NEI model indicates ionization equilibrium, we utilize the APEC model also. In applying these models to the data, we adopt the metal composition of Anders and Grevesse (1989) as the solar abundance. To represent interstellar absorption, we use the model PHABS on these emission models. In the course of the spectral fitting, we found that there remain wiggles in the fit residual. This is caused by the difference of gain among the CCD chips of MOS1/2 and the inaccuracy of calibration of the line spread function. Accordingly, we always use a Gaussian smoothing model (GSMOOTH in XSPEC) on the emission models. The errors quoted are always at the 90% confidence level.

4.1 North-eastern shell region

Figure 3a shows, with ellipses, regions 1 through 3 for collecting photons from the north-eastern shell, overlaid on the 0.3–10 keV MOS image.

The dashed ellipse is the background region. This region is taken symmetrical to regions 1 through 3 with respect to the peak of the center-filled brightness distribution of W 28 as well as to the optical axis position of the current field of view, in order to elucidate the nature of an excess emission from the shell.

The background-subtracted MOS spectra are shown in figure 3b, which combines readings of MOS1 and MOS2 from the 2002 and 2003 observations. The black, red, and blue crosses represent the data points from regions 1, 2, and 3, respectively. We have detected obviously He-like Kα emission lines from O (0.57 keV), Ne (0.91 keV), Mg (1.34 keV), Si (1.86 keV), and L lines of Fe around 1 keV. This means that the spectra include an optically thin thermal component. We therefore tried to fit the spectra with a single temperature non-equilibrium collisional ionization plasma emission model (VNEI model in XSPEC: Borkowski et al. 2001b; Hamilton et al. 1983; Borkowski et al. 1994; Liedahl et al. 1995) undergoing photoelectric absorption represented with a single hydrogen column density \( N_H \).

In the fitting, we set abundances of O, Ne, Mg, Si, and Fe free to vary but constrained to be common among the regions, because no statistically significant differences in the abundances are found among the regions in a trial fit. The abundances of the other elements are fixed at the solar values. The fitting is acceptable with the reduced \( \chi^2 \) of 0.91. As a result, however, we found an ionization parameter \( n_e t \) of \( \sim 10^{13} \, \text{cm}^{-3} \, \text{s} \), which indicates the shell plasma is in collisional ionization equilibrium. Accordingly, we replaced the VNEI model with a VAPEC model which represents a...
spectrum from a plasma in collisional ionization equilibrium. The best-fit parameters are summarized in table 1, and the best-fit models as well as the residuals are displayed in figure 3b. Note that we used both MOS and pn data for spectral fitting, although only MOS spectra are shown in figure 3b for clarity. The reduced $\chi^2$ of 0.85 implies that the fit is acceptable at the 90% confidence level. The temperatures are obtained to be $kT = 0.37^{+0.03}_{-0.03}$ keV, $0.30^{+0.02}_{-0.01}$ keV, and $0.28 \pm 0.01$ keV for regions 1, 2, and 3, respectively. The temperature decreases from north to south in the shell. We note that the temperatures we obtained are lower than those of $\sim 0.6$ keV in Rho and Borkowski (2002). The temperature difference should be due to the different background regions. The spectral analysis of the background region we used is shown in subsection 4.2. The hydrogen column density $N_H$ are $(6.2 \pm 0.5) \times 10^{21}$ cm$^{-2}$, $(8.2 \pm 0.3) \times 10^{21}$ cm$^{-2}$, and $(7.5 \pm 0.2) \times 10^{21}$ cm$^{-2}$ for regions 1, 2, and 3, respectively. The hydrogen column densities of regions 2 and 3 near the molecular cloud are higher than that of region 1. The abundances of O, Ne, Mg, Si, and Fe are lower than the solar values.

## 4.2 TeV $\gamma$-ray region

We investigated the X-ray spectrum of a region where intense TeV $\gamma$–ray emission is detected in spite of no apparent X-ray emission. Figure 4a shows the TeV $\gamma$-ray intensity contours [the same as in figure 2, Aharonian et al. (2008)] overlaid on the X-ray grayscale image. Although the TeV $\gamma$-ray surface brightness has a dual peak structure, we concentrated on the north-eastern peak, and extracted the source spectrum from the ellipse region located at $(l, b) \simeq (6.75, -0.30)$, as shown in figure 4a in green, because the southern peak centered at $(l, b) \simeq (6.56, -0.26)$ is partly included in the south-eastern rim and it is difficult to estimate non-thermal emission. The choice of the source integration region adopted here is also intended to exclude the thermal emission from the north-eastern shell region. The dashed ellipse in figure 4 is, on the other hand, a background region. Figure 4b shows the source and the background spectra thus extracted, from which the non-X-ray background (NXB) spectrum evaluated out of the telescope field of view are already subtracted. We have an excess below 2 keV, which may be stray light from the W 28 shell, which is very difficult to estimate correctly. Since we are interested in non-thermal emission associated with the TeV $\gamma$-ray emission, we hereafter use the data only in the 2–10 keV band.

The effective area of the background region is smaller than the source region due to telescope vignetting. We checked the vignetting effect by using the Lockman Hole archival data observed on 2002 December 27–29 (Obs ID = 0147511601) with the total effective exposure time of 110 ks. A count ratio of the background to source regions at the same detector positions was found to be 0.88 in the 2–10 keV band. In evaluating the flux of the possible

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**Table 1. Best-fit parameters of the north-eastern shell region spectra.**

| Parameters        | Region 1     | Region 2     | Region 3     |
|-------------------|--------------|--------------|--------------|
| Temperature [keV] | $0.37^{+0.05}_{-0.03}$ | $0.30^{+0.02}_{-0.01}$ | $0.28 \pm 0.01$ |
| Abundance$^*$     | $-0.01$     | $0.29^{+0.07}_{-0.05}$ | $-0.01$     |
| O                 | —           | —            | —            |
| Ne                | $0.33^{+0.06}_{-0.04}$ | $0.39^{+0.04}_{-0.05}$ | $0.39^{+0.06}_{-0.05}$ |
| Mg                | —           | —            | —            |
| Si                | $0.62^{+0.05}_{-0.01}$ | $0.62^{+0.05}_{-0.01}$ | $0.62^{+0.08}_{-0.01}$ |
| Fe                | —           | —            | —            |
| $EM^\dagger$      | $1.8^{+0.6}_{-0.5}$ | $1.0^{+0.5}_{-0.5}$ | $10^{2.5}_{-2.5}$ |
| $N_H^\dagger$     | $6.2 \pm 0.5$ | $8.2 \pm 0.3$ | $7.5 \pm 0.2$ |
| $g_{\text{smooth}}$ | —           | —            | —            |
| $\sigma$ (MOS)$^\ddagger$ | $0.11^{+0.06}_{-0.05}$ | $0.08^{+0.010}_{-0.033}$ | $0.09^{+0.020}_{-0.018}$ |
| $\sigma$ (pn)$^\ddagger$ | $0.11^{+0.09}_{-0.11}$ | $0.23^{+0.05}_{-0.05}$ | $0.17^{+0.03}_{-0.03}$ |
| index$^\ddagger$ | $1.0$ (fix) | $1.0$ (fix) | $1.0$ (fix) |
| $\chi^2$/d.o.f (reduced $\chi^2$) | $461.6/546$ (0.85) | $461.6/546$ (0.85) | $461.6/546$ (0.85) |

$^*$ Abundance ratio relative to the solar value (Anders & Grevesse 1989). The abundances are common over the regions.

$^\dagger$ Emission measure $EM = \int n_e n_d dV \simeq n_e^2 V$ in units of $10^{-6}$ cm$^{-3}$, where $n_e$ and $V$ are the electron density and the plasma volume. The distance to W 28 is assumed to be 1.9 kpc (Velázquez et al. 2002).

$^\ddagger$ Absorption hydrogen column density in units of $10^{21}$ cm$^{-2}$.

$^\ddagger$ Gaussian sigma at 6 keV in units of keV.

$^\ddagger$ Energy index of $\sigma$, i.e., $\sigma \propto E^{-\text{index}}$.

1. [http://hea-www.harvard.edu/APEC](http://hea-www.harvard.edu/APEC).
non-thermal X-ray emission, we first made an arbitral model of the background spectrum to reconstruct the background emission in the source region. Note that it is a mixture of Galactic ridge emission, cosmic X-ray background, and position-dependent NXB, so the resultant parameters have no physical meaning. Two power-law models showed an accepted fit with the photon indices of 0.85 and −5.8, as shown in figure 4c. The source spectrum was fitted with a model comprising of the two power-law models with the normalizations being multiplied by the vignetting correction factor, and an additional power-law model representing the putative non-thermal X-ray emission, with the frozen photon index of 2.66 which is the same as that in the TeV γ-ray band (Aharonian et al. 2008). Consequently, we only obtained an upper limit for the non-thermal X-ray emission. The 90% upper limit flux in the 2–10 keV band is obtained to be $2.1 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$.

5 Discussion

5.1 The nature of the low temperature thermal component

We found the $\sim$ 0.3 keV thermal emission from the north-eastern shell of W28 and determined the plasma parameters. Table 2 summarizes the electron density ($n_e$), the number of electrons ($N_e$), the mass, and the thermal energy ($E_{\text{thermal}}$) on the basis of the best-fit parameters summarized in Table 1.

We assume that the distance to W28 is 1.9 kpc (Velázquez et al. 2002), and the plasma distributes uniformly along the line of sight. The shapes of the emitting regions are assumed to be ovals with the line-of-sight extent being the same as the semi-minor axis appearing on the image ($r_b$). The volumes are calculated to be equal to $(4/3)\pi r_l^2 r_b$, where $r_l$ is the length of the semi-major axis on the image. With the aid of the emission measure $(EM = \int n_e n_H dV)$ obtained from the spectral fitting and $V$, we calculated $n_e$, taking into account $n_e \approx 1.24 n_H$ for fully ionized solar abundance plasma. The number of electrons ($N_e = n_e V$), the total mass, and the thermal energy [$E_{\text{thermal}} = \frac{3}{2}(N_e + N_H + N_{He}) kT$] were obtained under the assumption of energy equipartition between electrons and ions. The total thermal energy should be larger if other portions of the remnant are included, and if the proton temperature is significantly larger than the electron temperature as is expected for supernova remnants with large shock velocities (Ghavamian et al. 2007).

![Image](https://example.com/image.png)

**Fig. 4.** Integration regions and resultant spectra of the north-eastern TeV γ-ray peak. (a) The source and background integration regions are drawn in green. They are ellipses with semi-major and semi-minor axes of 6.6 and 1.9, respectively. (b) The source (black) and background (red) spectra with the MOS instruments. The NXB spectrum extracted from out of the field of view is already subtracted. The source spectrum below 2 keV is contaminated by the thermal emission from the north-eastern rim. (c) MOS background spectrum with the best-fit model. (Color online)

| Regions | $V$ [cm$^3$] | $n_e$ [cm$^{-3}$] | $n_et$ [10$^{11}$ cm$^{-3}$ s]$^3$ | $N_e$ [10$^{58}$] | Mass [M$_\odot$] | $E_{\text{thermal}}$ [10$^{48}$ erg] |
|---------|--------------|-----------------|-------------------------------|-----------------|-----------------|----------------------------------|
| 1       | $1.3 \times 10^{55}$ | 4.2$^{+0.7}_{-0.6}$ | 98 (> 4) | 0.54$^{+0.09}_{-0.08}$ | 0.044$^{+0.008}_{-0.007}$ | 0.090$^{+0.019}_{-0.015}$ |
| 2       | $1.4 \times 10^{55}$ | 9.4$^{+0.9}_{-0.9}$ | 11 (> 6) | 1.3$^{+0.1}_{-0.1}$ | 0.11$^{+0.01}_{-0.01}$ | 0.18$^{+0.02}_{-0.02}$ |
| 3       | $1.7 \times 10^{55}$ | 13$^{+1}_{-1}$ | 50 (> 9) | 2.1$^{+0.2}_{-0.2}$ | 0.17$^{+0.01}_{-0.01}$ | 0.27$^{+0.02}_{-0.02}$ |
| Total   | $4.4 \times 10^{55}$ | — | — | 3.9$^{+0.4}_{-0.4}$ | 0.32$^{+0.03}_{-0.03}$ | 0.54$^{+0.06}_{-0.06}$ |

$^a$Volumes were calculated on the assumption of an oval shape. See the text for more detail.

$^b$Electron densities were obtained by using $EM$ and the volume.

$^c$Ionization parameters ($n_et$) were found from the spectral fitting with a VNEI model as explained in section 4.
The temperature and the electron density of the northeastern shell regions are plotted in figure 5. The value of $n_e$ is much higher in the northeastern shell regions ($\sim 10^{3}$ cm$^{-3}$: Rho & Borkowski 2002). In particular, shell region 3, which apparently interacts with a molecular cloud (see figures 1 and 2), has the largest $n_e$. The higher-temperature region has lower density. This is probably because the original ejecta energy is distributed among a larger amount of interstellar matter for higher-density regions, as indicated by the total mass in the table.

5.2 Origin of the TeV $\gamma$-ray emission

We obtained the upper limit of the X-ray flux from one of the TeV $\gamma$-ray emission peaks, as described in subsection 4.2. Figure 6 shows the spectral energy distribution of the TeV $\gamma$-ray and the X-ray flux upper limit in the region. The red line is the TeV $\gamma$-ray power-law spectrum (Aharonian et al. 2008) with a photon index of 2.66, while the blue line is the upper limit of the X-ray power-law spectrum with a photon index assumed to be the same as that in the TeV band. The TeV flux is normalized to that of the X-ray flux by taking the difference in the integration region into account [the X-ray region is the $6.6 \times 1.9$ ellipse while the TeV $\gamma$-ray one in Aharonian et al. (2008) is a circle with a radius of 11.8]. The corrected TeV $\gamma$-ray flux is $3.3 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ in the 1–10 TeV band.

The flux ratio between 1–10 TeV and 2–10 keV ($F_{\text{TeV}}/F_X$) is often used to examine the emission origin (Yamazaki et al. 2006). In young SNR and pulsar wind nebula (PWN) cases, the value is in the range of $\sim 10^{-3}$–1 (Matsumoto et al. 2007; Bamba et al. 2007), whereas the value is larger than 16 in our case. This result implies that the $\gamma$-ray emission mechanism is different between young SNRs/PWN and our case of an old supernova remnant. Another sample is HESS J1745−303, which has an $F_{\text{TeV}}/F_X$ of larger than 4 (Bamba et al. 2009). The nature of this source is still unknown, but there is a molecular cloud and an old SNR G359.1−0.5 (Bamba et al. 2000b; Ohnishi et al. 2011).

Such a high value of $F_{\text{TeV}}/F_X$ is similar to that of sources called “dark particle accelerators” which are $\gamma$-ray sources without any X-ray counterparts (Matsumoto et al. 2007; Bamba et al. 2007). Although their nature is still unknown, one possibility can be old SNRs interacting with molecular clouds like W 28 and HESS J1745−303.

Here, we consider the emission origin more precisely using wideband spectrum. We first assume that the TeV $\gamma$-ray emission is powered through 1-zone IC scattering of the cosmic microwave background off the accelerated primary electrons, and the same electrons emit synchrotron radiation in the X-ray band. The characteristic energies
Fig. 7. Spectra of hadronic emissions with the age, the distance, and the number density of molecular cloud of $t_{\text{age}} = 3000\text{yr}$, $D = 1.9\text{kpc}$, and $n_{\text{mc}} = 1000\text{cm}^{-3}$, respectively. Emissions are $\pi^0$-decay $\gamma$-ray (solid line), bremsstrahlung (dot-dashed line), and synchrotron (dashed line) emission from secondary electrons produced by charged pions. Total emissions are shown by the bold line. The blue and red lines show the upper limit X-ray and TeV $\gamma$-ray spectra. (a) With proton number index $p = 2.66$, maximum proton energy $E_{\max,p} = 1000\text{TeV}$, total energy $E_{\text{total}} = 3.0 \times 10^{47}\text{erg}$, and magnetic field $B \lesssim 800\text{\mu G}$. (b) With $p = 2.0$, $E_{\max,p} = 40\text{TeV}$, $E_{\text{total}} = 8.1 \times 10^{45}\text{erg}$, and $B \lesssim 1500\text{\mu G}$. (Color online)

of a synchrotron photon $\epsilon$ and of an IC photon $E$ produced by the same electron are related as

$$\epsilon \simeq 0.07 \left(\frac{E}{1\text{\ TeV}}\right) \left(\frac{B}{10\text{\ \mu G}}\right) [\text{keV}]$$

$$f_X \simeq 10 \ f_{\text{TeV}} \left(\frac{B}{10\text{\ \mu G}}\right)^2$$

where $B$ is the magnetic field and $f$ is the flux (Aharonian et al. 1997). We draw synchrotron X-ray spectra with various magnetic fields ($B = 0.1, 1.0,$ and $10.0\text{\ \mu G}$) in figure 6 with dashed lines. We only obtained the upper limit of the magnetic field of $\lesssim 5\text{\ \mu G}$. This might be a little too weak for an efficient particle acceleration region (Vink & Laming 2003; Bamba et al. 2005, for example), although it is possible that electrons accelerated in the past escape from the acceleration region and emit IC photons in the observed position where the magnetic field is weak. However, the TeV $\gamma$-ray emission region coincides well with the distribution of the molecular cloud, as demonstrated in section 3 (figure 2). These facts suggest that the TeV $\gamma$-ray emission originates from pion decay triggered by impacts of the high-energy protons with the molecular clouds.

We then calculate a spectral energy distribution from X-ray to TeV $\gamma$-ray bands based on the pion decay. In this calculation, the TeV $\gamma$-ray originates from the process $\pi^0 \rightarrow \gamma + \gamma$, where $\pi^0$ is produced through collisions between an accelerated proton and a proton in a molecular cloud. Accordingly, the resultant $\gamma$-ray spectrum depends on an energy distribution function of the accelerated protons

$$\frac{dN}{dE} = C E^{-p} \exp \left(-\frac{E}{E_{\max,p}}\right) \ (E_{\min,p} < E < E_{\max,p})$$

and the density of the molecular cloud, where the energy $E$ in this context means the total energy. Here we set the minimum energy as the proton rest mass ($E_{\min,p} = m_p c^2$). It is well known that the resultant $\gamma$-ray energy is proportional to that of the bombarding proton (Drury et al. 1994), and hence we can simply adopt the number index $p$ to be equal to the photon index of the observed TeV $\gamma$-ray spectrum ($\sim 2.66$). We assume the distance to W 28 to be $1.9\text{kpc}$ (Velázquez et al. 2002) to constrain the normalization $C$. The density of the molecular cloud is measured from the CO observation (Arikawa et al. 1999), which is $10^3\text{cm}^{-3}$. With these parameters, we fitted the observed TeV $\gamma$-ray spectrum, and found that $E_{\max,p} \sim 10^{15}\text{eV}$. The total energy of the accelerated protons is obtained to be $3.0 \times 10^{47}\text{erg}$, which is much smaller than the supernova explosion energy ($\sim 10^{51}\text{erg}$). We have assumed a continuous and a homogeneous distribution of cosmic rays in time and space, respectively, in the molecular cloud. The result is displayed in figure 7a. Note that non-thermal bremsstrahlung originating from secondary electrons produced through collisions between the accelerated protons and the molecular cloud neutrons contribute significantly to the resultant spectrum, although it dominates somewhat
lower energy. Actually, Abdo et al. (2010c) discussed that the bremsstrahlung-dominated emission model requires an unrealistically low magnetic field. Given $E_{\text{max}, p}$ and the energy distribution of the secondary electrons, which can be calculated from that of the protons, and the absence of the synchrotron X-ray emission, we can set the upper limit on the magnetic field strength. By referring to the upper limit of the X-ray flux, we have obtained $B \lesssim 800 \mu G$. We remark that this upper limit of the magnetic field was obtained by setting $E_{\text{max}, p} = 10^{15}$ eV. In the case of $E_{\text{max}, p} > 10^{15}$ eV, the model synchrotron spectrum is enhanced and extends to higher energy without being cut off in the X-ray band. Consequently, a weaker magnetic field is required for the model synchrotron X-ray spectrum to be accommodated with the X-ray flux upper limit. The upper limit of $B = 800 \mu G$ is therefore the most conservative one in the case of $p = 2.66$. The $B = 800 \mu G$ case is shown in figure 7a. The parameters obtained are summarized in table 3. We note that, at the old SNR shocks with low shock velocity, the maximum energy of accelerated particles is smaller due to the escape of high-energy protons (e.g., Ohira et al. 2010). We have thus tried to calculate the spectrum in the case that the number index of the proton is equal to the canonical value of the Fermi acceleration ($p = 2.0$) in the lower-energy side. In this case, we adjust $E_{\text{max}, p}$ so that the resultant model spectrum can be fitted to the observed TeV $\gamma$-ray spectrum. The result of the maximum-$B$ case is shown in figure 7b. The maximum proton energy is found to be $E_{\text{max}, p} = 40$ TeV, and the total proton energy is $8.1 \times 10^{45}$ erg, which is again much smaller than the supernova explosion energy. The upper limit of the magnetic field strength is $B \lesssim 1500 \mu G$.

### Table 3. Physical parameters obtained with hadronic model fitting.

| Parameter                                | Case (a) | Case (b) |
|------------------------------------------|----------|----------|
| Maximum proton energy ($E_{\text{max}, p}$) [TeV] | $\gtrsim 1000$ | 40 |
| Total energy ($E_{\text{total}}$) [erg]    | $3.0 \times 10^{47}$ | $8.1 \times 10^{45}$ |
| Magnetic field ($B$) [$\mu G$]            | $\lesssim 800$ | $\lesssim 1500$ |
| Photon flux in the 0.1–1 GeV [photons cm$^{-2}$ s$^{-1}$] | $2.3 \times 10^{-8}$ | $6.3 \times 10^{-10}$ |
| in the 1–100 GeV [photons cm$^{-2}$ s$^{-1}$] | $4.1 \times 10^{-9}$ | $1.6 \times 10^{-10}$ |

The X-ray emission from the north-eastern shell is found to reach a collisional ionization equilibrium state and can be fitted well with a single temperature optically thin thermal emission model with $kT$ of $\approx 0.3$ keV. From the emission measure and the apparent volume, the electron density is found to be as high as $\approx 10$ cm$^{-3}$. Since a portion of a molecular cloud spatially coincides with the outer edge of a part of the shell, this high density is due to the collision of the plasma with the molecular cloud.

In contrast, there is no significant X-ray emission from one of the TeV $\gamma$-ray peaks. We only obtained the 90% upper limit flux of $2.1 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ in the 2–10 keV band, assuming a power-law spectrum with the same photon index as in the TeV $\gamma$-ray ($= 2.66$). The spatial coincidence of the molecular cloud and the TeV $\gamma$-ray emission site suggests that the TeV $\gamma$-ray is of hadronic origin. We calculated the spectra of hadrons including pions, kaons, nucleons, and so on produced through proton–proton scatterings and their daughter particles (gamma-rays, electrons, neutrinos, and so on), and found that $\pi^0$-decay emission is dominant in the TeV $\gamma$-ray band. A weak upper limit on the magnetic field strength is obtained at $B \lesssim 1500 \mu G$ from the X-ray flux upper limit.

### 6 Conclusion

We analyzed the XMM-Newton data of the north-eastern part of the supernova remnant W 28. The observed X-ray image showed the bright and twisted north-eastern shell and the inner emission region which is part of the center-filled emission brightening toward the south-west end of the field of view.

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