Discovery of a Hard X–ray Spectrum from the Mixed Morphology SNR W28 with *XMM-Newton*

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Abstract

We report on the discovery of a non-thermal X–ray emission from the supernova remnant (SNR) W28. W28 is a cosmic ray accelerator from which GeV and TeV γ–ray were detected. We analyzed the northeast part of W28, and found a power-law spectrum with a photon index of 2.4 (2.1–2.8) from an inner region which is probably non-thermal X–ray emission caused by particle acceleration. On the assumption that it is synchrotron X–ray, the cooling time of synchrotron photon is consistent with the age of W28 with a few μG magnetic field. On the other hand, we have no significant X–ray flux from one of the TeV γ–ray emission region. Assuming a power-law spectrum with a photon index of 2.66, the same as in the TeV band, we obtained a 2–10 keV flux upper limit of 2.1×10^{-14} ergs/s cm^2. Low brightness in X–ray and the coincidence of the molecular cloud and TeV γ–ray emission site suggests that TeV γ–ray is originated from accelerated protons.

Key words: acceleration of particles — ISM: individual (W28) — ISM: supernova remnants — X–ray: ISM

1. Introduction

Shocks of SNRs are one of the most promising acceleration sites of cosmic rays up to $\sim 10^{15.5}$ eV. The evidence of particle acceleration can be obtained with X–ray observation as a synchrotron emission or a non-thermal bremsstrahlung by high energy electrons. On the other hand, TeV γ–ray is also a clue of cosmic ray acceleration. TeV γ–ray emitted from SNR is explained by (1) Inverse-Compton scattering (IC) of cosmic microwave background photons or non-thermal bremsstrahlung by high energy electrons, or (2) the decay of neutral pions that are generated by collisions between high energy protons and dense interstellar matter.

The SNR W28 is an interesting target as a cosmic ray accelerator from which GeV and TeV γ–ray were detected from the eastern edge of the radio shell (Abdo et al. 2009; Aharonian et al. 2008). The interaction with the molecular cloud was also revealed by a lot of OH Masers (Claussen et al. 1997), which are signposts of molecular interactions, and by the location of high density shocked gas (n>10^4 cm^{-3}; Arikawa et al. 1999). W28 locates at (l, b) = (6.4°, -0.1°) with a radius, a distance and an age of 48 arcmin, 1.9 kpc and several times 10^4 yr, respectively.

2. Data Analysis

The northeast part of W28 was observed with *XMM-Newton* with the total effective exposure time of ~50 ksec for MOS and ~40 ksec for pn, respectively.

2.1. Image

In figure 1, the combined image are shown which comprehend 0.3–2.0 keV gray scale X-ray image, the molecular cloud in blue, TeV γ–ray in yellow contours, the position of OH masers in white points and the 95% confidence region of GeV emission detected with *Fermi* in yellow circle. 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 occurs there. The eastern and southern molecular clouds coincide with the TeV γ-ray emission sites, where the surface brightness of the X–ray emission is low. The GeV emission is also detected from the southern peak of the TeV γ-ray (Abdo et al. 2009).

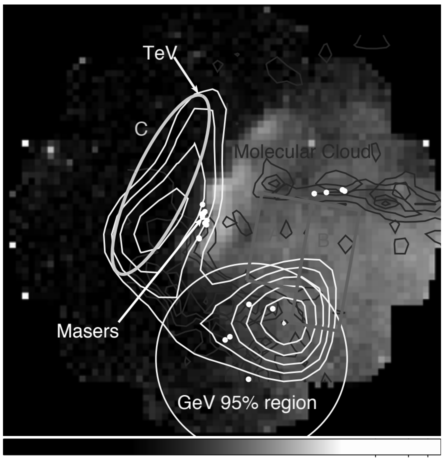

Fig. 1. X-ray image overlaid on the molecular cloud, TeV γ-ray contours, OH Masers and 95% confidence region of GeV emission. Extracted spectrum regions are shown in aqua.

2.2. Spectrum

We searched the entire field of view of the current W28 observation for non-thermal X–ray emission, and discovered it from the inner regions A and B in figure 1. Figure 2 shows the background subtracted spectra obtained with MOS1 + MOS2 as well as the best-fit spectral models. We fitted the spectra with 2 temperature non-equilibrium collisional ionization plasma model ("vnei" model in XSPEC; Borkowski et al. 2001) for the thermal components, and with a power-law model for the hard tail. The best-fit parameters are shown in table 1. The photon index of power-law component is 2.4 (2.1–2.8) for both regions, and summed 2–10 keV flux was obtained to be 5.8 (4.2–7.0)$\times10^{-13}$ erg/cm^{2}s.

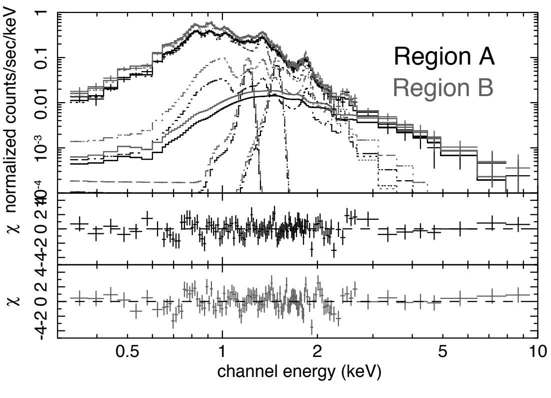

Fig. 2. Spectra of region A and B with MOS1 + MOS2.

On the other hand, we detected no significant X–ray emission from region C, where intense TeV γ–ray emission is detected. Assuming a power-law model with a photon index of 2.66, which is obtained with TeV γ–ray spectrum (Aharonian et al. 2008), we obtained a 2–10 keV upper limit flux of 2.1$\times10^{-14}$ erg/cm^{2}s.

Table 1. Best fit parameters of region A and B spectra

Non-thermal component	
Photon index	2.4 (2.1–2.8)
2-10 keV Flux [ergs/cm^{2}s]	5.8 (4.2–7.0)$\times10^{-13}$
Thermal component	
kT$_1$ [keV]	0.33 (0.29-0.37)
kT$_2$ [keV]	0.94 (0.70–1.2)
Electron density [/cc]	0.65 (0.53–0.90)
χ^2/d.o.f (Reduced χ^2)	507/519 (0.98)

3. Discussion

3.1. On the origin of hard X–ray spectrum

Let us consider the emission mechanism of the non-thermal component detected from region A and B.

If the emission is a synchrotron X-ray, a cooling time ($t_{\rm cool}$) of the electron is

$$t_{\rm cool} = 4.7\times10^4\left(\frac{B}{1\,\mu{\rm G}}\right)^{-1.5}\left(\frac{\epsilon}{1\,{\rm keV}}\right)^{-0.5}\ [{\rm yr}] \quad (1)$$

where ϵ is a synchrotron photon energy. With a few μG magnetic field, $t_{\rm cool}$ is consistent with the age of W28. Thus the observed power-law X–ray emission can be interpreted as the synchrotron emission from primary electrons. Synchrotron X-ray by secondary electrons which is produced by the decay of neutral pions is not likely because of no detection of non-thermal X-ray from the molecular cloud region. Non-thermal bremsstrahlung is difficult because it requires too large energy density of non-thermal electrons.

3.2. The relation with TeV γ–ray emission

The upper limit 2–10 keV flux was obtained to be 2.1$\times10^{-14}$ ergs/cm^{2}s in region C. We found the flux ratio between 1–10 TeV to 2–10 keV of >16. On the assumption that the TeV γ–ray was emitted by IC of CMB from high energy electrons, we can determine the upper limit magnetic field of $<3\mu$G from this upper limit. In addition, the TeV γ–ray emission regions well coincide with the distribution of the molecular cloud, as demonstrated in § 2.1. All these facts strongly suggest that the observed TeV γ–ray is due to the decay of neutral pions generated by the high energy proton impacts.

References

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