Non-Thermal and Supra-Thermal X-Rays from the Northeast Shell of W28

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Abstract

We observed the northeast X-ray shell of an SNR W28 with *XMM-Newton* and found two X-ray bright spots; one is interacting with a molecular cloud, and the other is free from the interaction. The X-ray spectra from these regions show emission lines and a hard tail, and are fitted with a model of a thin-thermal plasma ($kT \sim 0.3$ keV) plus a power-law function. The abundances are lower than the solar value, which suggests the presence of additional featureless continuum emission, possibly a non-thermal component. We also found that the hard X-rays are extending to the center region of the SNR (the inside region). The X-ray spectrum is different from those of the shell region; it requires three-temperature (~ 0.3, ~ 0.6, and > 4 keV) plasma.

1. Introduction

EGRET found GeV-gamma rays from several galactic supernova remnants (SNRs; W28, W44, IC443, etc.) [1]. The emission mechanism, however, is still not well known. These SNRs have several common characteristics. The most important feature may be the association of OH masers and excited CO-lines, which suggests the presence of SNR-cloud interaction. Hence the GeV-gamma ray emission would be the consequence of the SNR-cloud interaction.

W28 (G6.4−0.1) is a bright radio SNR [2]. The CO-line observation suggested that the northwest shell is interacting with a molecular cloud [3]. Our earlier analysis of the *ROSAT* and *ASCA* data found that the northeast X-ray shell correlates well with the CO-line intensity map. Many OH masers are also found just outside the X-ray shell [4]. In order to study the SNR plasma under the SNR-cloud interaction and to search for any connection between the cloud-SNR interaction and the GeV-gamma emissions, we observed this region with the high throughput X-ray observatory, *XMM-Newton*.

2. Observation and Data Reduction

XMM-Newton [5] observed the northeast shell of W28 on September 23, 2002. The effective exposure time is approximately 18 ks. The data were acquired with the thick filter in full image mode. The raw data were converted to cleaned

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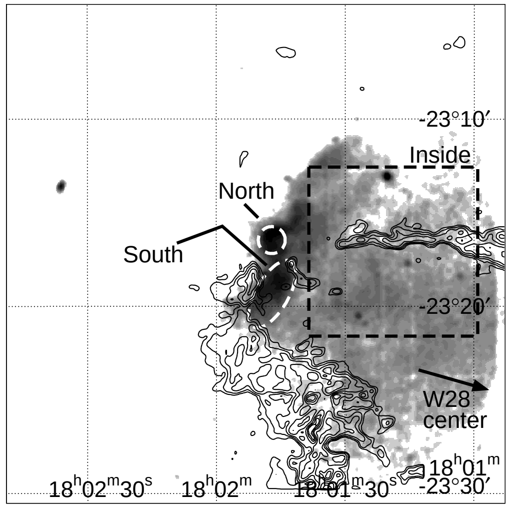

Fig. 1. *XMM-Newton* image (0.5−7.0 keV) of the north-east shell of W28, overlaid on the CO (J=3−2) intensity contours. The spectral regions are shown with the dashed lines.

event lists using the Standard Analysis System (SAS) software (version 5.4.1). The X-ray images and spectra were extracted from the event lists, using only the single and double events.

3. Data Analysis

Fig.1 shows the EPIC image in the 0.5−7.0 keV band overlaid on the intensity contours of CO ($J = 3 - 2$) emission excited by the SNR shock [3]. We find two bright X-ray spots in the shell; the "South" region is interacting with the molecular cloud, while the "North" region is free from the interaction. In the hard X-ray image (2.0−7.0 keV), we find that the X-rays are rather smoothly extending toward the center of the SNR (the inside region). We extracted the X-ray spectra from the three regions shown in Fig. 1.

Since both the spectra of the North and South regions show emission lines from highly ionized atoms and a hard tail (Fig. 2(a,b)), we fitted the spectra with a model of a thin thermal plasma (APEC; [6]) plus a power-law function. The best-fit models and parameters are shown in Fig. 2(a,b) and Table 1 (the error regions indicate 90% confidence levels in this paper).

The spectrum of the inside region (Fig. 2(c)) also shows emission lines and a hard tail as is the case of the shell spectra. We further find a line-like structure at ~ 2.5 keV, a K-shell transition energy of H-like sulfur, which can be produced in a very high temperature plasma. We therefore fitted the spectrum with a two-temperature (~ 0.3 and > 2 keV) thin thermal plasma model. Although this model represents the overall feature, we still find a data excess near at the Si K-shell emission with χ^2/degree of freedom (d.o.f.)$= 471/322$. We thus tried an

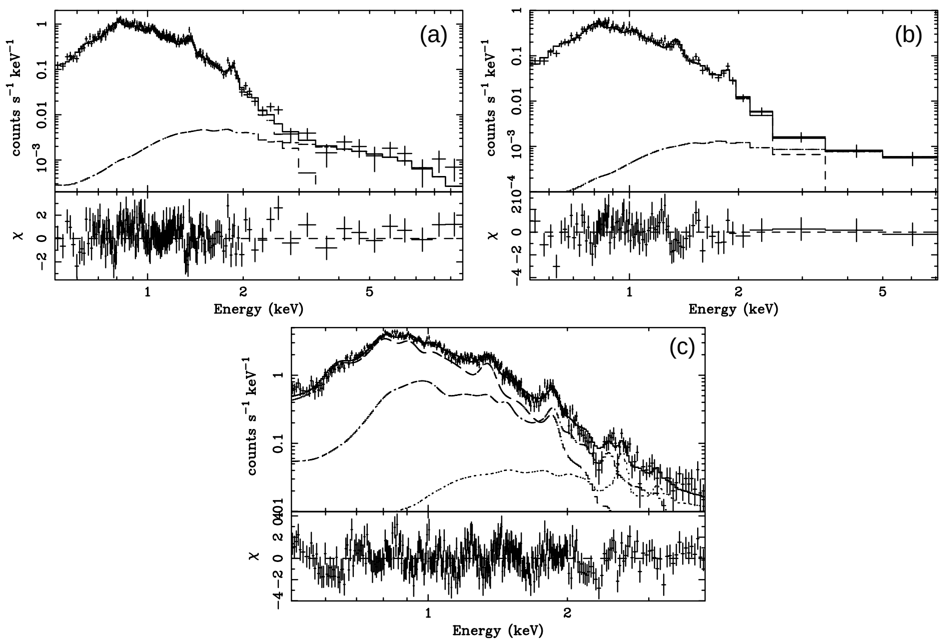

Fig. 2. EPIC/PN spectra of the South (a), the North (b), and the inside (c) regions.

additional thermal component, and the χ^2/d.o.f. is largely reduced to 412/320. The best-fit model is shown in Fig. 2(c). The temperatures of the three thermal components are 0.28 $(0.26-0.30)$, 0.63 $(0.60-0.71)$, and 7.9 (>4.1) keV.

4. Discussion

4.1. The Interacting Region

Since the South and North regions are near the shell of an old SNR (the age of W28 is $\sim 4\times10^4$ yr [7]), the plasma would mainly due to the interstellar gas (not the ejecta). Hence the chemical abundances should be nearly solar. However the best-fit abundances are significantly smaller than the solar values. Furthermore, the abundances from the South region is only 60% of the North regions, although the best-fit temperatures are nearly the same with each other.

One may argue that the chemical abundances of the cloud is fur less than the solar, and the abundance deficient in the South region may be explained by the dilution effect due to the cloud SNR interaction. In this case, however, the plasma temperature should be lower than the North region (free from the interaction), which is conflicting with the observed results.

As one possible explanation for the apparent abundance deficient, we propose that the continuum spectra are not purely thermal but are contaminated by non-thermal emission. We accordingly fit the spectra with a model of solar abundance plasma adding a power-law continuum. Then we obtain reasonable fit with the photon index ~ 6. This putative power-law emission contaminates more the South than the North spectra.

Table 1. Spectral parameters of the South and North regions.

Parameter	South region	North region
APEC:		
kT(keV)	0.29 (0.29−0.30)	0.30 (0.29−0.31)
Abundance[a] ..	0.23 (0.18−0.27)	0.39 (0.28−0.53)
norm[b] ($\times 10^{12}$)	4.7 (4.2−5.6)	1.2 (1.1−1.8)
power-law:		
Photon index	1.3 (0.4−1.9)	1.3 (fixed)
norm[c] ($\times 10^{-5}$)	1.3 (0.4−3.0)	0.41 (0.28−0.58)
$N_{\rm H}$(10^{21} cm^{-2}) .	8.0 (7.7−8.2)	7.8 (7.4−8.2)
χ^2/ d.o.f	396/323	177/161

a: Abundances relative to solar. b: $(n_e n_H V)/4\pi D^2$.
c: Photons/keV/cm^2/s at 1 keV.

4.2. The Steep Power-law Component and the Hard X-rays

When we add the same power-law component of photon index $\sim$ 6 to the spectral model of the inside region, the fit is further improved (χ^2/d.o.f.= 378/318). Thus the steep power-law component may be prevailing all over W28 including the inner region. The origin of the power-law continuum would be synchrotron emission with a break energy less than the typical synchrotron SNR such as SN1006. In fact, the synchrotron emission in the radio band ($\sim$ 46 Jy at 328 MHz and $\sim$ 35 Jy at 1415 MHz; see [8]) can be smoothly connected to this X-ray component. The larger fraction of the power-law emission in the South compared to the North is probably the consequence that the particle acceleration is more effective in the former region due to the large magentic field in the cloud.

The hard X-rays ($>$ 2 keV) are also clearly seen in the spectra of both the shell regions and the inside region. The temperature corresponding to the hard X-rays is significantly higher than a typical plasma in an old SNR. Therefore the hard X-rays may be due to the bremsstrahlung of a supra-thermal plasma, or the low energy end of accelerated electrons.

5. Reference

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