Non-Thermal Emission from an X-Ray Shell near at 30 Dor C

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Abstract

We analyzed the Chandra archival data of a shell-like source found near at 30 Dor C (here 30 Dor C) in the SN 1987A observations. The shell radius is ~ 3 arcmin or ~ 40 pc at a distance of 50 kpc for the Large Magellanic Cloud (LMC). This large radius places 30 Dor C to be one of the oldest X-ray SNRs in the LMC. The south-east shell exhibits line emission and is fitted with a thin thermal model. The explosion energy is estimated to be $\sim 7 \times 10^{51}$ erg s^{-1}, consistent with or larger than that of a typical supernova. A remarkable discovery is featureless spectra from the northern and western part of the shell. The spectra are fitted with a power-law model of photon indices $2.3 - 2.7$. We thus argue that 30 Dor C is the first extragalactic SNR with the synchrotron X-ray dominated shell.

1. Introduction

Since the discovery of cosmic rays (Hess 1912), the origin and acceleration mechanism have been long-standing problems. A breakthrough came from the X-ray studies of SN 1006; Koyama et al. (1995) discovered synchrotron X-rays from the shell of this SNR, which is the evidence for the existence of extremely high energy electrons up to ~ 10 TeV. Furthermore, Tanimori et al. (1998) confirmed the nature by detecting the inverse Compton γ-ray emission from SN 1006. Now, several Galactic SNRs have been identified as acceleration sites of high energy cosmic rays: G347.3−0.5 (e.g., Koyama et al. 1997; Enomoto et al. 2002), RCW 86 (Bamba et al. 2000; Borkowski et al. 2001), and G266.2−1.2 (Slane et al. 2001).

Whether the acceleration at the shells of SNRs can explain most of the cosmic ray flux or not is a remaining problem. In order to study the acceleration quantitatively, the Large Magellanic Cloud (LMC) is one of the best places. The relative closeness and well-determined distance of the LMC allows us to determine

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Table 1. Observation Log

Observation ID	On axis position (RA, DEC)(J2000)	Date (yyyy/mm/dd)	Exposure (ksec)
1044	$(05^{h}35^{m}22^{s}, -69°16'33'')$	2001/04/25	18
1967	$(05^{h}35^{m}22^{s}, -69°16'33'')$	2000/12/07	99

physical properties of each SNR in the galaxy. Besides, the low absorption column density toward the galaxy enable us to detect soft X-rays (0.5−2.0 keV), the key band to study thermal properties of SNRs.

Mills et al. (1984) found a shell-like structure in the southwest of 30 Dor (the brightest H II region in the LMC) in the radio band (843 MHz) and named as 30 Dor C. Dennerl et al. (2001) observed this region with *XMM-Newton* and found a complete ring with a ∼6 arcmin diameter. Itoh et al. (2001) found hard X-ray emission from 30 Dor C with *ASCA*. However, the poor spatial resolution of *ASCA* could not determine whether the hard emission is non-thermal or not. In this paper, we report on discovery of non-thermal X-ray emission from the shell of 30 Dor C with *Chandra*.

2. *Chandra* Observation

2.1. Data

Chandra has observed SN 1987A for several times using the ACIS-S array. Some observations cover the 30 Dor C region, which is at the northeast of SN 1987A. In order to study the diffuse structures of 30 Dor C, we chose two observations with no grating. The log of these observations is listed in Table 1.

2.2. Image and spectra

We made soft (0.7–2.0 keV) and hard (2.0–7.0 keV) band images (Fig. 1) by superposing the two observations and correcting for the exposure. We see a clear shell with a diameter of ∼ 6 arcmin corresponding to ∼ 80 pc at the distance of 50 kpc. The western side is harder than the eastern side. We can also see other SNRs in the images, the Honeycomb nebula (SNR 0536−69.3) and SN 1987A.

We extracted spectra from regions A–D shown in Fig. 1(a), excluding point sources in these regions. The spectra of the regions B–D are featureless and hard, indicating non-thermal emission, while the spectrum of the region A shows many line structures and is soft, indicating thermal origin.

To determine the thermal property first, we proceeded fitting of the spec-

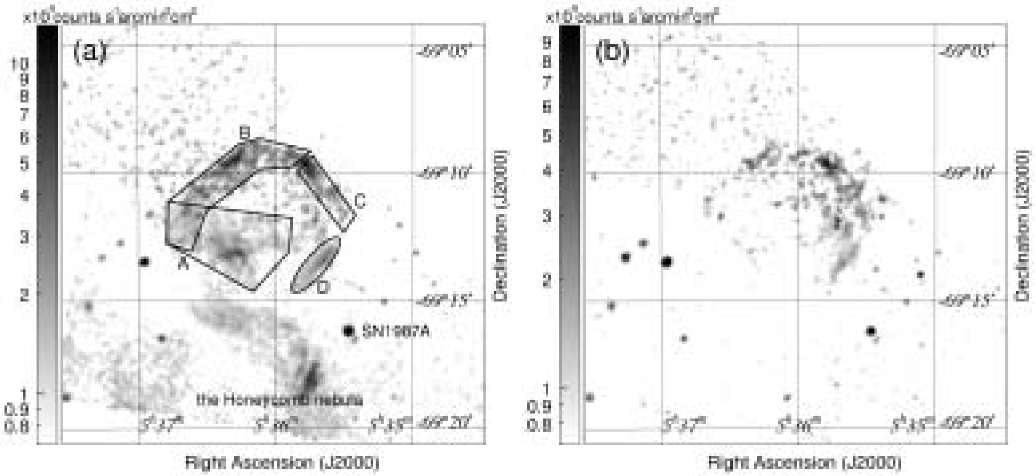

Fig. 1. The soft (0.7–2.0 keV; (a)) and hard (2.0–7.0 keV; (b)) band images.

trum of the region A. K-lines of He-like and H-like of Ne and Mg seen in Fig. 2(a) can not be explained with a single NEI plasma. Therefore, we fitted the spectrum with a two-temperature NEI model, and found this model is acceptable with χ^2/degree of freedom (d.o.f) = 77/80. The best-fit model and parameters are shown in Fig. 2 and Table 2. The errors correspond to 90% confidence levels hereafter. The high and low temperature components can be attributed to the forward and reverse shocks respectively. We also tried a model consisting of a single-temperature NEI and a power-law, but this model was statistically rejected (χ^2/d.o.f = 131/95). This indicates that the plasma with the relatively high temperature ($\sim$1.4 keV) really exists in 30 Dor C.

The spectra of the regions B–D were fitted with a model consisting of two NEI components and a power-law model. The temperatures and the abundances of the two NEI components were fixed to those of the spectrum of the region A, while the normalizations are free parameters. The model is acceptable (Fig. 2) with the best-fit parameters shown in Table 3. These spectra are dominated by the power-law component, attributable to synchrotron emission by high energy (>1 TeV) electrons like SN 1006.

3. Discussion

3.1. Information from other wavelengths

In the optical to infrared bands, high-mass star clusters were found inside 30 Dor C, near the center and in the northern part of 30 Dor C (e.g., Testor et al. 1993). Spectroscopy at [SII] and Hα revealed shocked gas at 30 Dor C (Mathewson

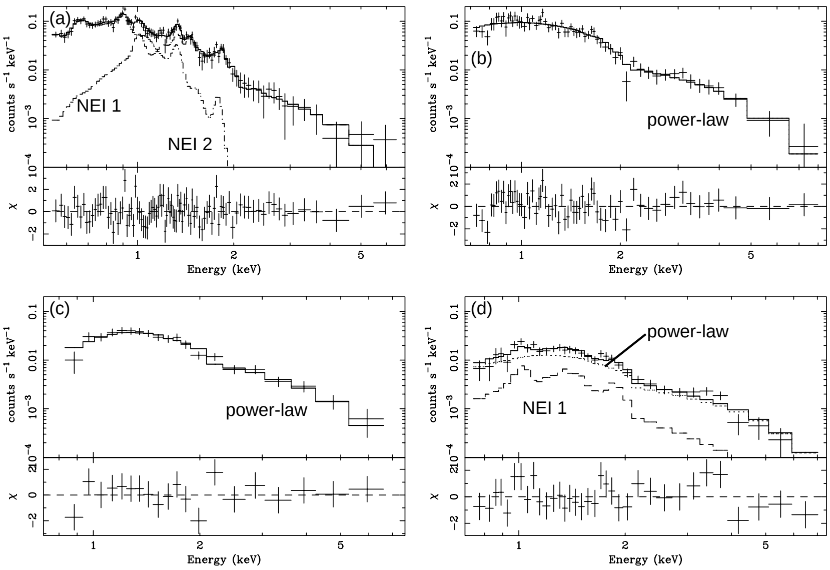

Fig. 2. The background-subtracted spectrum of each region ((a):A (b):B (c):C (d):D).

et al. 1985). The small flux ratio between these lines (0.3) suggested that the the shock speed is not as high as a young or medium aged SNR. We, however, found the high temperature plasma with X-rays. Therefore, the existence of high speed shock (SNR) is established. Radio continuum observations have shown synchrotron emission from moderately high energy electrons (e.g., Mathewson et al. 1985) of morphology nicely coincident with our hard X-rays.

3.2. Explosion energy and age of the supernova

We estimate the explosion energy of the progenitor(s) through the Sedov solution on the assumption that 30 Dor C is in an adiabatic expansion phase at the distance of 50 kpc. As we mentioned in section 3.1, we attribute the high temperature component ($kT = 1.4$ (1.0–2.1) keV) of the region A to the forward shock plasma. Then, the age (t) and the ratio of the explosion energy (E) to the ambient density (n) are,

$$
\begin{aligned}
t &= 1.8\ (1.5 - 2.1) \times 10^{4}\ D_{\rm 50kpc}\ [\rm yr] && (1)\\
E/n &= 1.0\ (0.7 - 1.6) \times 10^{53}\ D_{\rm 50kpc}^{5/2}\ [\rm erg\ cm^{-3}] && (2)
\end{aligned}
$$

Since the age of the shocked plasma should be shorter than the SNR age,

$$
t_{\rm plasma} < t = 5.7\ (4.6 - 6.7) \times 10^{11}\ [\rm s] \qquad (3)
$$

Table 2. The best-fit parameters for the region A

Parameter	NEI1	NEI2
kT [keV]	1.4 (1.1–2.1)	0.14 (0.11–0.16)
$\log(n_{\rm e}t)$ [cm^{-3}s]	11.2 (10.8–11.9)	> 13.3
$EM^{\dagger}$ [10^{58} cm^{-3}]	1.7	680
$N_{\rm H}$ [10^{21} cm^{-2}]	5.8 (5.2–7.3)	5.8 (5.2–7.3)
Abundance‡:		
O	0.19 (fixed)	0.02 (0.01–0.04)
Ne.............	0.65 (0.30–2.68)	0.08 (0.06–0.14)
Mg	0.57 (0.35–0.90)	0.56 (0.05–1.24)
Si	0.37 (0.22–0.58)	0.31 (fixed)
S	0.018 (< 0.034)	0.36 (fixed)
Fe	0.00 (< 0.04)	0.36 (fixed)

†: Emission measure $EM = \int n_{\rm e} n_{\rm H} {\rm dV}$ assuming the distance $\sim$ 50 kpc.
‡: Abundances are relative to solar values (Anders & Grevesse 1989). Abundance of some elements are fixed to the average values in the LMC (Russel & Dopita 1992; Hughes et al. 1998).

From the NEI model,

$$n_{\rm e} t_{\rm plasma} = 1.6\ (0.63 - 7.9) \times 10^{11}\ [{\rm cm^{-3}\ s}] \quad (4)$$

$$n_{\rm e} > 0.28\ (0.094 - 1.7)\ [{\rm cm^{-3}}] \quad (5)$$

For the compression ratio of 4,

$$n \sim n_{\rm e}/4 > 0.070\ (0.023 - 0.43)\ [{\rm cm^{-3}}] \quad (6)$$

By substituting this value into the equation (2),

$$E = 1.0 \times 10^{53}\ D_{\rm 50kpc}^{5/2} \times n > 7.0\ (1.6 - 43) \times 10^{51}\ [{\rm erg}] \quad (7)$$

Although the error is relatively large, the most probable value is significantly larger than the Type-Ia supernova explosion energy of 1×10^{51} erg. Therefore the explosion would be either a single supernova leaving a black-hole or multiple supernovae. Both of these scenarios require high mass stars, and are consistent with the existence of the high-mass star clusters near the center of 30 Dor C.

3.3. Non-thermal emission

The photon indices of the regions B, C, and D are within the range of 1.9–3.1 including the 90%-confidence region. These values are similar to those

Table 3. The best-fit parameters for the regions B, C, and D

Parameter	B	C	D
$EM_1^\dagger$ [10^{58} cm^{-3}]....	0.0 ($<$ 0.24)	0.0 ($<$ 0.54)	0.18 (0.03-0.31)
$EM_2^\dagger$ [10^{61} cm^{-3}]....	0.0 ($<$ 1.3)	0.0 ($<$ 3.0)	0.0 ($<$ 0.033)
Power-law:			
Photon index	2.5 (2.3−2.8)	2.7 (2.2−3.1)	2.3 (1.9−2.7)
Flux‡ [erg s^{-1} cm^{-2}]	1.0 $\times 10^{-12}$	8.1$\times 10^{-13}$	2.0 $\times 10^{-13}$
$N_{\rm H}$ [10^{21} cm^{-2}]......	1.8 (1.0−8.0)	8.0 (6.4−18.2)	5.2 (3.9−7.3)
χ^2/d.o.f	55.8/58	15.0/15	31.5/30

†: Emission measures of NEI 1 and NEI 2 components.

‡: Absorption corrected flux in the 0.7−10.0 keV band.

observed in the well-established SNRs as acceleration sites of high energy electrons (e.g., SN 1006 (Koyama et al. 1995); G347.3−0.5 (Koyama et al. 1997)).

The total luminosity (0.7−10.0 keV) of the non-thermal X-rays mounts to 6.0×10^{35} erg s^{-1}. This value is $\sim$ 10 times larger than that of SN 1006, or a large number of high energy electrons are accelerated in 30 Dor C. The exceptionally large explosion energy (section 3.2) would be attributable to the energetic acceleration in the medium aged SNR of $\sim 10^4$ yr.

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