Discovery of Non-thermal X-rays from the Shells of 30 Dor C with *Chandra*

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Abstract

We discovered non-thermal X-ray shells from 30 Dor C in the Large Magellanic Cloud (LMC) with *Chandra*. The radius of the shell is $\sim 3'$, ~ 40 pc at the LMC distance of 50 kpc. From the shell-like morphology, 30 Dor C is likely an SNR. The spectra of the north and west shells show no line-like structure and well fitted with a power-law model of photon index = 2.3–2.5, suggesting a non-thermal origin. Therefore, this is the first detection of non-thermal X-ray shells, or an SN 1006-like SNR from an extragalactic system. The X-ray shell is the largest among known SN 1006-like SNRs with the luminosity of $\sim 7 \times 10^{35}$ ergs s^{-1}.

1 Introduction

Since the discovery of cosmic rays (Hess 1912), the origin and acceleration mechanism up to $10^{15.5}$ eV 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, suggesting the existence of extremely high energy particles up to the knee energy accelerated by the first order Fermi process. Now, several Galactic SNRs have been suggested to be acceleration sites of high energy cosmic rays.

These discoveries, however, are limited only in our Galaxy, and it is unclear whether or not such SNRs are observed in extragalactic systems. Also, we have no systematic information on SN 1006-like SNRs in a galaxy; how many such SNRs are there?, or what fractions of cosmic rays are accelerated in a galaxy? Due to the large absorption through the Galactic plane, such a systematic study is not suitable in our Galaxy, but is more suited in an extragalactic system. Therefore, the next breakthrough should be made by the discovery of an SN 1006-like SNR from a galaxy outside of the Milky Way.

30 Dor is the brightest H II region in the LMC and the active star formatting region. Mills et al.(1984) found a shell-like structure in the southwest of 30 Dor in the 843 MHz band and named as 30 Dor C. The spectral index of the source changes from position to position in the shell, which arises confusion whether it is a single or multiple SNRs. Dennerl et al.(2000) observed the structure with *XMM-Newton* and found that it appears as a complete ring of $\sim$3 arcmin radius. With the *ASCA* observations, Itoh et al.(2001) detected hard X-rays from 30 Dor C, however due to the limited spatial resolution, they could not conclude that the emission is from the shells of 30 Dor C.

2 Observations and Data Reduction

ObsID	On axis position (J2000) (hhmmss.s, ddmmss.s)	Exposure [ks]
1044	(05:35:22.30, -69:16:33.6)	18
1967	(05:35:35.21, -69:16:13.7)	99

Table 1: The positions and exposure times in the observations.

We used the *Chandra* archival data of the ACIS observations targeted on SN 1987A (Observation ID = 1044 and 1967). The observed date and positions are in Table 1. The data reduction and analyses were made using the *Chandra* Interactive Analysis of Observations (CIAO) software version 2.2.1. The effective exposure of each observations is shown in Table 1.

3 Results

3.1 Images

The soft (0.7–2.0 keV) and hard band (2.0–7.0 keV) images around 30 Dor C are shown in Figure 1. Clear shell-like structure with the diameter of $\sim 340''$ is seen in both the bands, although the detailed morphology is different; the whole shell is seen in the soft band, whereas only west part emits hard X-rays. In the shell, some point source (A & B) and a clump in soft X-ray is seen. The other SNRs, Honeycomb nebula (SNR 0536−69.3) and SN 1987 A (Williams et al. 1999) are also seen in the soft band image.

3.2 Spectral Analyses

For the spectral analyses, we divided the shell into 4 regions as seen in Figure 1 and made the separate spectra. The spectra of the regions 2-4 are similar with each other and were fitted well with both a CIE thermal plasma model (Mewe et al. 1985) and a power-law function. The absorption column was calculated using the cross sections by Morrison and McCammon (1983) with solar abundances (Anders and Grevesse 1989). The best-fit parameters are shown in Table 2.

The spectrum of region 1, on the other hand,is softer and rejected single component model (Table 2). We hence tried the fitting of a two-component model, a CIE plasma plus power-law function. As a result, the reduced χ^2 became significantly smaller as shown in Table 3. The power-law index is essentially the same as those of sources 2-4, which suggests that the hard component is omnipresent in all the shell.

	parameters
Thermal component	
kT [keV]	$0.19^{+0.04}_{-0.02}$
abundance	1.0 (>0.8)
Flux† [ergs cm^{-2}s^{-1}]	6.9×10^{-14}
Non-thermal component	
Γ	$2.5^{+0.4}_{-0.3}$
Flux†[ergs cm^{-2}s^{-1}]	9.8×10^{-14}
$N_{\rm H}$ [10^{21} cm^{-2}]	$6.1^{+0.8}_{-1.1}$
reduced χ^2 [chi^2/d.o.f.]	154.7/123

†: In the 0.5 – 10.0 keV band.
‡: Errors refer to the 90% confidence level.

Table 3: Best-fit parameters for shell 1‡.

We also made the spectrum of the clump accumulating X-ray photons from a circle with the radius of $15''$. The spectrum is relatively soft with strong He-like Mg line, and is fitted with an absorbed CIE plasma model. The Mg abundance is free from the other elements. The fitting is marginally rejected with the reduced $\chi^2 = 20.9/14$ however the model well traces the emission. The best-fit temperature, abundance for Mg and the other elements, $N_{\rm H}$, and flux in the 0.5–10.0 keV band are $0.3^{+0.1}_{-0.1}$ keV, $0.5^{+1.6}_{-0.3}$, < 0.03, $< 1.9 \times 10^{21}$ cm^{-2}, and 3.4×10^{-14} ergs cm^{-2} s^{-1}, respectively.

For the point sources A & B, the radius of the source region are taken to be 6 times of the PSF. The power-law fits are acceptable with the best-fit parameters of $\Gamma = 4.4^{+4.1}_{-1.3}$, $N_{\rm H} = 3.3^{+2.6}_{-2.2} \times 10^{21}$ cm^{-2}, and the flux of 3.1×10^{-15} ergs cm^{-2} s^{-1} for A, and $\Gamma = 1.7^{+1.0}_{-0.6}$, $N_{\rm H} = 1.5^{+5.2}_{-1.5} \times 10^{21}$ cm^{-2}, and the flux of 7.0×10^{-15} ergs cm^{-2} s^{-1} for B.

4 Discussion

Since we can not conclude whether the hard emission from the shells of 30 Dor C is thermal or non-thermal from the spectral fit alone, we refer the data of the radio and Hα emission line band (Mathewson et al. 1985), and discuss the origin. The 843 MHz emission, which indicates the synchrotron emission from GeV electrons, has shell-like structure, very similar to the hard X-ray morphology. On the other hand, Hα emission, which is an indicator of the shocked gas, concentrates in the southeast region of the shell (around shell 1), which anti-correlates with the hard X-ray emission. Similar correlations can be seen in other synchrotron X-ray SNRs, SN 1006 (Winkler and Long 1997) and RCW 86 (Smith 1997). Therefore, we suggest that the hard X-rays are of non-thermal origin. This is the first discovery of SN 1006-like sources in an extragalactic system. The total non-thermal luminosity is 7×10^{35} ergs s^{-1}, about 10 times larger than that of SN 1006.

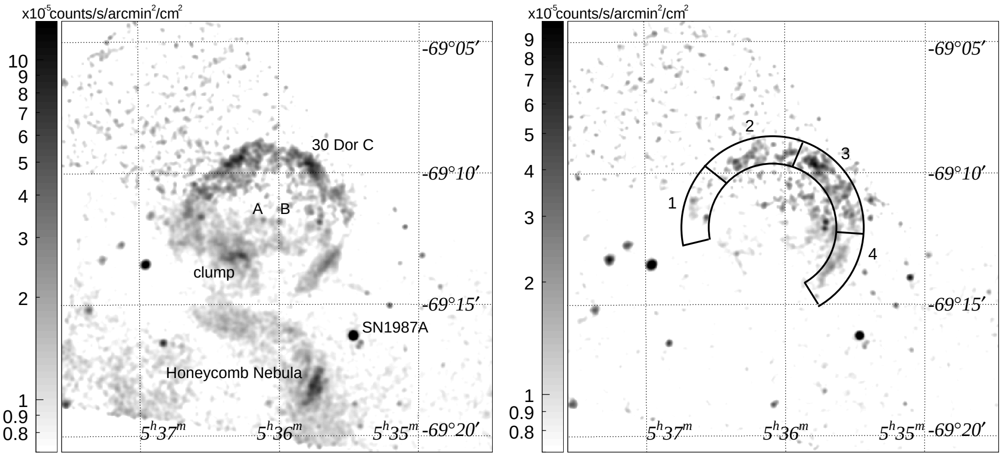

Figure 1: The images around 30 Dor C in the 0.7–2.0 keV band (left) and in the 2.0–7.0 keV band (right). The scale is logarithm in a unit of $\times 10^{-5}$ photons s^{-1} $arcsec^{-2}$ as shown in the left bar. The source region for spectral analyses and the source names are shown.

Parameters	shell 1	shell 2	shell 3	shell 4
Thermal model				
kT [keV]	$0.7^{+0.1}_{-0.1}$	$2.8^{+1.1}_{-0.7}$	$3.0^{+1.5}_{-0.9}$	$2.5^{+0.6}_{-0.5}$
Abundance	$0.04^{+0.01}_{-0.01}$	$0.33^{+0.67}_{-0.26}$	0.08 (<0.56)	$0.20^{+0.22}_{-0.14}$
$N_{\rm H}$ [10^{21} cm^{-2}]	$1.0^{+0.6}_{-0.4}$	$1.0^{+0.7}_{-0.7}$	$4.0^{+1.0}_{-0.8}$	$5.5^{+0.9}_{-0.8}$
Flux† [ergs $cm^{-2}s^{-1}$]	1.2×10^{-13}	5.2×10^{-13}	5.1×10^{-13}	2.0×10^{-13}
reduced χ^2 [χ^2/d.o.f.]	209.7/125	79.4/73	68.8/80	161.7/143
Non-thermal model				
Γ	$3.4^{+0.5}_{-0.4}$	$2.4^{+0.4}_{-0.2}$	$2.3^{+0.4}_{-0.3}$	$2.5^{+0.2}_{-0.2}$
$N_{\rm H}$ [10^{21} cm^{-2}]	$2.2^{+0.8}_{-0.7}$	$2.5^{+1.1}_{-0.8}$	$5.5^{+1.3}_{-1.1}$	$7.1^{+1.1}_{-0.9}$
Flux† [ergs $cm^{-2}s^{-1}$]	1.5×10^{-13}	5.5×10^{-13}	5.7×10^{-13}	2.1×10^{-13}
reduced χ^2 [χ^2/d.o.f.]	222.1/126	79.1/74	68.8/80	162.7/144

†: In the 0.5 – 10.0 keV band.
‡: Errors refer to the 90% confidence level.

Table 2: Best-fit parameters for spectral fittings‡.

We calculated the total explosion energy (E_{tot}) and the age (t) of 30 Dor C with the assumption of Sedov solutions and using the best-fit thermal parameters in shell 1. Assuming the shock width of $1/12R$, we derived $E_{tot} \sim 3 \times 10^{51}$ ergs and $t \sim 6 \times 10^4$ years, which implying that 30 Dor C may be a single SNR, although E_{tot} is slightly larger than that of the ordinary SNR. This source is also the biggest and oldest SN 1006-like SNR. The clump is located near at the OB star association NGC 2044 (Lortet & Testor 1986) hence is likely the X-ray counterpart. However the presence of strong Mg line and low temperature plasma favor an ejecta from SN explosion of 30 Dor C. More detailed observations must be needed to judge whether the clump is a part of the SNR or X-ray counterpart of NGC 2044.

The X-ray luminosities for the point sources A and B are 3.6×10^{33} ergs s^{-1} and 2.3×10^{33} ergs s^{-1} at 50 kpc, respectively. Source A has no counterpart within 5″, and has the X-ray luminosity comparable to the ordinary neutron stars, this may be a central neutron star in the SNR 30 Dor C, as already suggested by Dennerl et al.(2001). Source B coincides in position at a Wolf-Rayet star HD 269828E. The X-ray luminosity is also in the range of Wolf-Rayet star. Thus source B is very likely an X-ray counterpart of HD 269828E.

5 Conclusion

We found hard X-rays from the shells of 30 Dor C. The spectra are well fitted with a power-law function of $\Gamma = 2.3$–2.5 or an NEI plasma model of $kT = 2.5$–3.0 keV. The correlation with the radio emission and the anti-correlation with the Hα emission, together with the hard X-ray spectra, suggest that the emission is non-thermal

Then 30 Dor C is the first sample of SN 1006-like SNRs in an extragalactic system. The non-thermal luminosity, the radius, the explosion energy, and the age are the largest among previous SNR samples. To understand this unique source, more deep and broad band observations are needed.

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