Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 41 (2008) 383–389

Advances in Space Research
(a COSPAR publication)

www.elsevier.com/locate/asr

XMM-Newton observations across the Cygnus Loop from northeastern rim to southwestern rim

Satoru Katsuda *, Hiroshi Tsunemi

Department of Earth and Space Science, Graduate School of Science, Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka 560-0043, Japan

Received 22 November 2006; received in revised form 27 April 2007; accepted 3 May 2007

Abstract

We have observed the Cygnus Loop from the northeast (NE) to the southwest (SW) with XMM-Newton. We extracted spectra from 3′-spaced annular regions across the Loop and fitted them either with a one-kT_e-component non-equilibrium ionization (NEI) model or with two-kT_e-component NEI model. We found that the two-kT_e-component model yields significantly better fits in almost all the spectra than the one-kT_e-component model. Judging from the abundances, the high-kT_e-component in the two-temperature model must be fossil ejecta while the low-kT_e-component comes from the swept-up interstellar medium (ISM). The distributions of Ne, Mg, Si, and S for fossil ejecta appear to retain the onion-skin structure at the time of a supernova explosion, suggesting that significant overturning of the ejecta has not occurred yet. Comparing the relative abundances of fossil ejecta estimated for the entire Cygnus Loop with those from theoretical calculations for Type-II SN, the mass of the progenitor star is likely to be ~13 $M_\odot$. The trends of the radial profiles of kT_e and emission integral for the swept-up ISM are adequately described by the Sedov model, suggesting that the swept-up ISM is concentrated in a shell-like structure. Comparing our data with the Sedov model, we found the ambient medium density to be ~0.7 cm^{-3}. Then, we estimated the total mass of the swept-up ISM and the age of the remnant to be ~130 $M_\odot$ and 13,000 years, respectively. Note that if the explosion occurred within a stellar wind cavity, then the density in the cavity, the total swept-up mass in the cavity, and the age of the remnant are estimated to be ~0.14 cm^{-3}, ~25 $M_\odot$, and ~10,000 years, respectively.

Keywords: ISM: abundances; ISM: individual (Cygnus Loop); Supernova remnants; X-rays: ISM

1. Introduction

The Cygnus Loop is a typical middle-aged (5000 ~ 18,000 years, Blair et al., 1999; Rappaport et al., 1974) shell-like supernova remnant (SNR). The diameter is ~26 pc at a distance of 540 pc (Blair et al., 2005). Since it is an evolved SNR, the bright shell mainly consists of the swept-up interstellar medium (ISM) which overwhelms the ejecta-material from supernova (SN) explosion. Miyata et al. (1994) observed the northeast (NE) shell of the Loop with ASCA and revealed the metal deficiency there (Miyata et al., 1994). Since several previous measurements indicate that the ISM around the Cygnus Loop has metal deficient abundances (Dopita et al., 1977), they concluded that the plasma in the NE-shell is dominated by the ISM. Recent Suzaku observation of this region confirms the metal deficiency there (Miyata et al., 2007). In contrast to the shell region, ASCA detected strong emission lines from Si, S, and Fe–L in the center portion of this remnant (Miyata et al., 1998). The metal abundances of Si, S, and Fe are at least several times higher than those of the cosmic values. Compared with the metal abundances in the shell (Miyata et al., 1994), the over abundances of Si, S, and Fe in the center portion are much clearer: a few tens of times higher than those in the shell region. This is strong evidence that the fossil ejecta from the SN have been detected near the center of the Cygnus Loop.

In order to study the ejecta distribution as well as the overlying ISM, we observed the Cygnus Loop from NE

* Corresponding author. Tel.: +81 06 850 5476; fax: +81 06 850 5539.
E-mail address: katsuda@ess.sci.osaka-u.ac.jp (S. Katsuda).

0273-1177/$30
doi:10.1016/j.asr.2007.05.015

to southwest (SW) with the XMM-Newton satellite. Since the Cygnus Loop is very large in apparent size ($2.8 \times 3.5°$ Levenson et al., 1997), seven pointings are required to cover the Loop from NE-rim to SW-rim.

2. Observations

The XMM-Newton observations across the Cygnus Loop from NE to SW were performed in seven pointings (from pos-1 to pos-7) during the AO-1 phase. We concentrate on the data obtained with the EPIC MOS and PN cameras. All the data were obtained using medium filters and the prime full window mode. Fortunately, all the data other than pos-4 were free from background flares. Obs IDs, the observation date, and the effective exposure times after rejecting the high-background periods are summarized in Table 1.

All the raw data were processed with version 6.5.0 of the XMM Science Analysis Software (XMMSAS). We selected X-ray events corresponding to patterns 0–12 and 0 for MOS and PN, respectively. We further cleaned the data by removing all the events in bad columns listed in Kirsch (2006). After the filtering, the data were vignetting-corrected using the sas task `evigweight`. For the background subtraction, we employed the data set accumulated from blank sky observations prepared by Read and Ponman (2003). After adjusting its normalization to the source data in the energy range between 5 and 12 keV, where the emission is free from the contamination from known astrophysical sources (e.g., Fujita et al., 2004; Sato et al., 2005), we subtracted the background data from the source.

The right upper panel in Fig. 1 shows an exposure-corrected ROSAT HRI image of the entire Cygnus Loop with overlaid fields of view (FOV) of XMM-Newton. An XMM-Newton image of the merged MOS1/2, PN data from all the seven XMM-Newton observations is also shown in Fig. 1.

Table 1
Observational parameters for XMM-Newton observations of the Cygnus Loop

Obs. ID	Camera	Obs. date	Effective exposure (ks)
0082540101	MOS1	2002-11-25	14.1
	MOS2		14.1
	PN		5.6
0082540201	MOS1	2002-12-03	14.4
	MOS2		14.4
	PN		11.7
0082540301	MOS1	2002-12-05	11.6
	MOS2		11.6
	PN		9.1
0082540401	MOS1	2002-12-07	4.9
	MOS2		4.9
	PN		3.4
0082540501	MOS1	2002-12-09	12.6
	MOS2		12.6
	PN		10.0
0082540601	MOS1	2002-12-11	11.5
	MOS2		11.5
	PN		5.9
0082540701	MOS1	2002-12-13	13.5
	MOS2		13.5
	PN		7.5

3. Spatially resolved spectral analysis

Fig. 2 left shows two example spectra: black and red come from the entire FOV of pos-1 and pos-5, respectively. They are equalized in intensity at the O Heα line. We can see prominent emission lines from O Heα (0.5–0.6 keV), O Lyα (0.6–0.7 keV), Fe–L complex (0.7–0.85 keV), Ne Heα (0.85–0.95 keV), Mg Heα (1.3–1.4 keV), Si Heα (1.8–1.9 keV), and S Heα (2.4–2.5 keV) in the spectra. The two spectra are clearly different from one another especially in energy bands around Fe–L, Si–K, and S–K.

Miyata et al. (1994) performed spatially resolved spectral analysis for the NE-rim of the Cygnus Loop from annular regions with $3'$ thickness. They found that the temperature increased toward the center of the Loop. Therefore, we divided our FOV into $3'$-spaced annular rings which are similar to those by Miyata et al. (1994). regions whose center is located at ($20^h51^m34^s.699$, $31°00'00''$), i.e., the nominal position of pos-4. In this way, we extracted 53 X-ray spectra: the regions are numbered from -26 to $+26$, starting from the eastern rim and ending on the

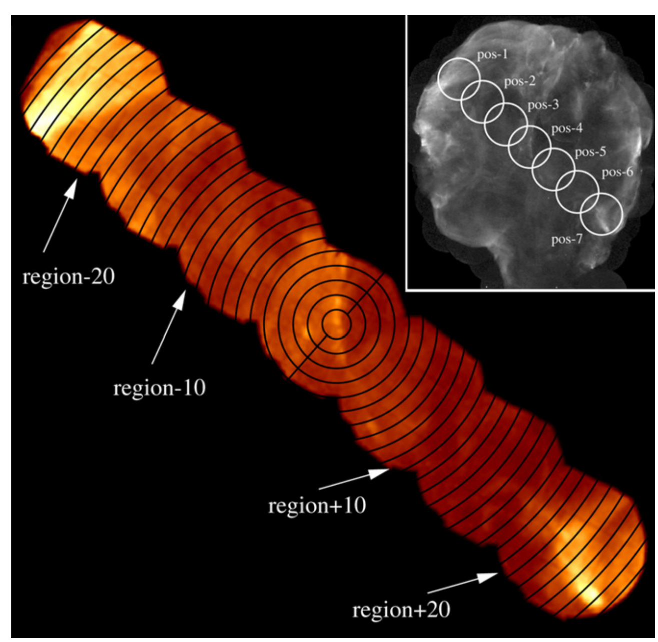

Fig. 1. XMM-Newton image of the merged MOS1/2, PN data from seven XMM-Newton observations. The annular regions where we extracted spectra are indicated by black solid lines. The thickness of each annular region is $3'$. Right-upper: ROSAT HRI image of the entire Cygnus Loop. The FOV of our XMM-Newton observations are indicated by while circles.