THE PLASMA STRUCTURE OF THE CYGNUS LOOP FROM THE NORTHEASTERN RIM TO THE SOUTHWESTERN RIM

HIROSHI TSUNEMI,1 SATORU KATSUDA,1 NORBERT NEMES,1 AND ERIC D. MILLER2

Received 2007 June 2; accepted 2007 September 5

ABSTRACT

The Cygnus Loop was observed from the northeast to the southwest with XMM-Newton. We divided the observed region into two parts, the north and the south path, and studied the X-ray spectra along the two. The spectra can be well fitted either by a one-component nonequilibrium ionization (NEI) model or by a two-component NEI model. The rim regions can be well fitted by a one-component model with relatively low $kT_e$ whose metal abundances are subsolar ($0.1 - 0.2 Z_\odot$). The major part of the paths requires a two-component model. Because of projection effects, we conclude that the low-$kT_e$ ($\sim 0.2$ keV) component surrounds the high-$kT_e$ ($\sim 0.6$ keV) component, with the latter having relatively high metal abundances ($\sim 5$ times solar). Since the Cygnus Loop is thought to have originated in a cavity explosion, the low-$kT_e$ component thus originates from the cavity wall, while the high-$kT_e$ component originates from the ejecta. The flux of the cavity-wall component shows a large variation along our paths. We find it to be very thin in the southwest region, suggesting a blowout along our line of sight. The metal distribution inside the ejecta exhibits nonuniformity, depending on the element: O, Ne, and Mg are relatively more abundant in the outer region, while Si, S, and Fe are concentrated in the inner region, with all metals showing strong asymmetry. This observational evidence implies an asymmetric explosion of the progenitor star. The abundance of the ejecta also indicates that the progenitor mass was about 15 $M_\odot$.

Subject headings: ISM: abundances — ISM: individual (Cygnus Loop) — supernova remnants — X-rays: ISM

1. INTRODUCTION

A supernova remnant (SNR) reflects the abundance of the progenitor star when the remnant is young and that of the interstellar matter (ISM) when it becomes old. In this way, we can study the evolution of the ejecta and the ISM. The Cygnus Loop is a prototypical middle-aged, shell-like SNR. The angular diameter is about $2.4\degree$, and it is very close to us (540 pc; Blair et al. 2005), implying a diameter of $\sim 23$ pc. The estimated age is about 10,000 yr, less than half the value based on the previous distance estimate of 770 pc (Minkowski 1958).

Since the Cygnus Loop is an evolved SNR, the bright shell mainly consists of the shock-heated surrounding material. Its supernova (SN) explosion is generally considered to have occurred in a preexisting cavity (McCray & Snow 1979). Levenson et al. (1997) found that the Cygnus Loop is the result of a cavity explosion that was created by a star of spectral type no later than B0. It is almost circular in shape, with a breakout in the south where the hot plasma extends out of the circle. Miyata et al. (1994) observed the northeast shell of the loop with the Advanced Satellite for Cosmology and Astrophysics (ASCA) and revealed a metal deficiency there. Since Dopita et al. (1977) had reported a metal deficiency of the ISM around the Cygnus Loop, Miyata et al. concluded that the plasma in the northeast shell is dominated by the ISM. Because of the constraints of the detector efficiency, they assumed that the relative abundances of C, N, and O were equal to the solar value (Anders & Grevesse 1989). More recently, Miyata et al. (2007) used the Suzaku satellite (Mitsuda et al. 2007) to observe one pointing position in the northeast rim. They detected emission lines from C and N and determined the relative abundances. They concluded that the relative abundances of C, N, and O are consistent with the solar values whereas the absolute abundances show a depletion from solar. Katsuda et al. (2008) observed four pointings in the northeast rim and detected a region where the relative abundances of C and N are a few times higher than that of O.

Hatsukade & Tsunemi (1990) detected a hot plasma inside the Cygnus Loop, which is not expected in the simple Sedov model. They reported that the plasma was confined inside the Loop. Miyata et al. (1998) detected strong emission lines of Si, S, and Fe L from inside the Loop. They found that the metal abundance is at least several times higher than solar, indicating that it is higher than that of the shell region by a factor of a few tens. They concluded that the metal-rich plasma is a fossil of the SN explosion. The abundance ratios of Si, S, and Fe indicated the progenitor star’s mass to be $25 M_\odot$. Miyata & Tsunemi (1999) measured the radial profile inside the Loop and found a discontinuity around 0.9$R_s$, where $R_s$ is the shock radius. They measured the metallicity inside the hot cavity, and they estimated the progenitor mass to be $15 M_\odot$. Levenson et al. (1998) estimated the size of the cavity and the progenitor mass to be $15 M_\odot$. Therefore, the progenitor of the Cygnus Loop was a massive star, in which the triple-$\alpha$ reaction should have dominated rather than the CNO cycle. If the material surrounding the Cygnus Loop is contaminated by the stellar activity of the progenitor star, it may explain the C abundance inferred for this region with Suzaku (Katsuda et al. 2008).

In order to study the plasma conditions inside the Cygnus Loop, we observed it from the northeast rim to the southwest rim with the XMM-Newton satellite. We report here the result, covering a full diameter with seven pointings.

2. OBSERVATIONS

We performed seven pointing observations of the Cygnus Loop, so that we could cover the full diameter from the northeast rim to the southwest rim (“Pos-1” to “Pos-7”), during the XMM-Newton AO-1 observing cycle. We concentrate on the data obtained with the EPIC MOS and pn cameras. All the data were taken...
using medium filters and the prime full-window mode. Fortunately, all the data other than those from Pos-4 suffered very little from background flares. Observation IDs, the observation date, the nominal aim point, and the effective exposure times after rejecting high-background periods are summarized in Table 1.

All the raw data were processed with version 6.5.0 of the XMM Science Analysis System (SAS). 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 the EPIC documentation (Kirsch 2006). After filtering the data, they were vignetting-corrected using the SAS task *evigweight*. For the background subtraction, we employed a data set accumulated from blank-sky observations prepared by Read & Ponman (2003). After adjusting its normalization to the source data by using the energy range between 5 and 12 keV, where the emission is free from contamination (Fujita et al. 2004; Sato et al. 2005), we subtracted the background data set from the source.

### 3. SPATIALLY RESOLVED SPECTRAL ANALYSIS

#### 3.1. Band Image

Figure 1 displays an exposure-corrected ROSAT High Resolution Imager (HRI) view of the entire Cygnus Loop (black and white) overlaid with the XMM-Newton color images of the merged MOS1, MOS2, and pn data from all the XMM-Newton observations. In this figure, we allocated color codes as red (0.3–0.52 keV), green (0.52–1.07 keV), and blue (1.07–3 keV). One can see that the outer regions are reddish rather than bluish, while the central region is bluish.

The northeast rim is the brightest in our field of view (FOV), showing a bright filament oriented 45° to the radial direction corresponding to NGC 6992. The southwest rim, where there is a V-shaped structure (Aschenbach & Leahy 1999), is also bright in our FOV. In the center of the Loop, an X-ray–bright filament runs through Pos-4 and Pos-5, forming a circular structure. This can be seen in the ROSAT image, where it forms a large circle within the Cygnus Loop. Thus, there are many fine, bright filaments in intensity. However, we find that there is a clear intensity variation along our scan path, dim in the center and bright at the rim.

Figure 2 shows spectra for the seven pointings; each is a sum over the entire FOV. The northeast rim (Pos-1) and the southwest rim (Pos-7) show strong emission lines below 1 keV, including O, Fe L, and Ne, while the center (Pos-4) shows strong emission lines from Si and S. One can see that the equivalent widths of the Si and S emission lines are larger in the center and gradually decrease toward the rim. We compare the spectra from Pos-1 and Pos-4 in Figure 3. Prominent emission lines are O Heα, O Lyα, the Fe L complex, Ne Heα, Mg Heα, Si Heα, and S Heα. The emission-line shapes for O are quite similar to each other, while there is a large difference at higher energies. Since the spectrum from the northeast rim can be well modeled as a single-temperature plasma (Miyata et al. 1994), we need an extra component in the center.

#### 3.2. Radial Profile

Although there are many fine structures, no matter how finely we might divide our FOV, each region would contain different plasma conditions due to the integration of the emission along the line of sight. Therefore, we concentrate on large-scale structure along the scan path. First of all, we divided our FOV into two parts along the diameter: the north path and the south path. Then we divided these into many small annular sectors, whose center is located at 20h51m34.7s,3 1°00′00″ (J2000), the nominal center of Pos-4. There are 141 and 172 annular sectors for the north and south paths, respectively. These small sectors, shown in Figure 1, are divided such that each has at least 60,000 photons (~20,000 for MOS1/2 and ~40,000 for pn), to equalize the statistics. We extracted the spectrum from each sector using the data set accumulated from blank-sky observations as sky background.

### Table 1

**Summary of the Observations**

| ObsID          | Observation Date | R.A.  | Decl. | Camera | Effective Exposure (ks) |
|----------------|------------------|-------|-------|--------|-------------------------|
| 0082540101     | 2002 Nov 25      | 20 55 23.6 | +31 46 17.0 | MOS1  | 14.1                     |
| 0082540201     | 2002 Dec 3       | 20 54 07.4 | +31 30 51.4 | MOS1  | 14.4                     |
| 0082540301     | 2002 Dec 5       | 20 52 51.1 | +31 15 25.7 | MOS1  | 11.6                     |
| 0082540401     | 2002 Dec 7       | 20 51 34.7 | +31 00 00.0 | MOS1  | 4.9                      |
| 0082540501     | 2002 Dec 9       | 20 50 18.4 | +30 44 34.3 | MOS1  | 4.9                      |
| 0082540601     | 2002 Dec 11      | 20 49 02.0 | +30 28 16.1 | MOS1  | 10.0                     |
| 0082540701     | 2002 Dec 13      | 20 47 45.8 | +30 13 42.9 | MOS1  | 13.5                     |

**Note:** Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
We have confirmed that the emission above 3 keV is statistically zero. In this way, we obtained 313 spectra. These sectors can be identified by their angular distance, $R$, from the center (east is negative and west is positive, as shown in Fig. 1).

The width of each sector depends on $R$. They range from 3.8$^\circ$ to 0.2$^\circ$ in the north path and from 3.0$^\circ$ to 0.2$^\circ$ in the south path. The widest sectors are in Pos-4 because of its short exposure, due to a background flare. The narrowest sectors are in the north-east rim, where the surface brightness is the highest.

### 3.3. Single-Temperature NEI Model

We fitted the spectrum for each sector with an absorbed nonequilibrium ionization (NEI) model with a single $kT_e$, using models wabs (Morrison & McCammon 1983) and vnei (NEI ver. 2.0; Borkowski et al. 2001) in XSPEC version 12.3.1 (Arnaud 1996). We fixed the column density, $N_{\text{H}}$, to 4.0 $\times$ 10$^{20}$ cm$^{-2}$ (see, e.g., Inoue et al. 1980; Kahn et al. 1980). Free parameters were $kT_e$, the ionization timescale $\tau$ (a product of the electron density and the elapsed time after the shock heating), the emission measure (EM = $\int n_e n_i \, dl$, where $n_i$ and $n_e$ are the number densities of hydrogen and electrons and $dl$ is the plasma depth), and the abundances of C, N, O, Ne, Mg, Si, S, Fe, and Ni. We set the abundances of C and N equal to that of O, that of Ni equal to Fe, and those of the nonfree elements fixed to their solar values (Anders & Grevesse 1989). In the fitting process, we took 20 as the minimum number of counts in each spectral bin to perform a $\chi^2$ test. We determined the value of the minimum counts that did not affect the fitting results. Figure 4 shows the distribution of the reduced $\chi^2$ (black) as a function of $R$ along both the north path and the south path. We found that the values of the reduced $\chi^2$ for all the sectors are between 1.0 and 2.0. If we take into account a systematic error of 5% (Nevalainen et al. 2003; Kirsch 2006), the reduced $\chi^2$ is around 1.5 or less.

In general, the values of the reduced $\chi^2$ are a little higher in the central part of the Cygnus Loop. Miyata et al. (1994) observed the northeast rim with ASCA and found that the spectra could be well represented with a one-temperature VNEI model with a temperature gradient toward the inside. The Suzaku observation of the northeast rim (Miyata et al. 2007) reveals that the X-ray spectrum can be represented by a two-temperature model: one component is 0.2–0.35 keV and the other is 0.09–0.15 keV. In our fitting, the value of $kT_e$ obtained is 0.2–0.25 keV. Therefore, we detect the hot component that Suzaku detected. There may be an additional low-temperature component, which seems difficult to detect with XMM-Newton because of its relatively lower sensitivity below 0.5 keV compared with Suzaku.

The ASCA observation (Miyata et al. 1994) also shows that the northeast rim is metal-deficient. Those authors concluded that the plasma in the northeast rim consists of ISM rather than ejecta. This is confirmed by the Suzaku observation (Miyata et al. 2007), which indicates C, N, and O abundances of $\sim$0.1, 0.05, and 0.1 times solar, respectively. We also find a metal deficiency in the data from the northeast rim; the best-fit results are given in Figure 5 (left) and Table 2. Leahy (2004) measured the X-ray spectrum of the southwest region of the Cygnus Loop and reported that the oxygen abundance there is about 0.22 times solar. Therefore, the X-ray measurements of the Cygnus Loop show that the metal abundances are depleted.

Cartledge et al. (2004) measured interstellar oxygen along 36 sight lines and confirmed the homogeneity of the O/H ratio within 800 pc of the Sun. One of their measurements was in a direction about 5$^\circ$ from the Cygnus Loop. The oxygen abundance they measured is about 0.4 times the solar value (Anders & Grevesse 1989). Wilms et al. (2000) employed 0.6 of the total interstellar abundances for the gas-phase ISM oxygen abundance and suggested that this depletion may be due to grains. Although the
ISM near the Cygnus Loop may be depleted, the abundances are still much higher than what we obtain at the rim of the Cygnus Loop. It is difficult to explain such a low abundance of oxygen in material originating from the ISM. Therefore, the origin of the low metal abundance is open to question. Since the Cygnus Loop is thought to have exploded in a preexisting cavity, we can say that the cavity material shows a low metal abundance. The abundance difference between our data and those from Suzaku may be due to the difference in detection efficiency at low energies. Taking into account projection effects, the plasma in the rim regions consists only of cavity material, while that of the inner regions consists of both cavity material and an extra component filling the interior of the Loop.

3.4. Two-Temperature NEI Model

To further constrain the plasma conditions, we applied a two-component NEI model with different temperatures. In this model, we add an extra component to the single-temperature model. The extra component is also an absorbed VNEI model with $kT_e$, $\tau$, and EM as free parameters. The metal abundances of the extra component are fixed to those determined at the northeast rim, so that the extra component represents the cavity material. Figure 4 shows the reduced $\chi^2$ values (red) along the path. Applying an

![Fig. 2.—MOS1 spectra for the seven pointings; each is a sum over the entire FOV.](image)

![Fig. 3.—Comparison of spectra between Pos-1 (circles) and Pos-4 (triangles). The spectra are equalized in intensity at O He$\alpha$.](image)

![Fig. 4.—Distribution of the reduced $\chi^2$ as a function of distance $R$ along the north path (top) and the south path (bottom). The single-component model is shown in black, and the two-component model is shown in red.](image)
Looking at the image in detail, there are fine structures with the two-component model. This is partly due to systematic
Therefore, we considered that the outer sectors (|R| > 70') can be safely represented with a one-component model, while the other sectors can be represented by a two-component model. In this way, we performed the analysis by applying a two-component VNEI model with different temperatures. We assume that the low-temperature component comes from the surrounding region of the Cygnus Loop and that the high-temperature component occupies the interior of the Loop.

We found that the values of the reduced $\chi^2$ are 1.0–1.8 even with the two-component model. This is partly due to systematic errors. Looking at the image in detail, there are fine structures within the sector. Furthermore, the spectrum from each sector is an integration along the line of sight. Since we only employ two VNEI plasma models, the values of the reduced $\chi^2$ are mainly due to the simplicity of the plasma model employed here. Therefore, we think that the plasma parameters obtained will represent typical values in each sector.

**TABLE 2**

| Parameter | Value |
|-----------|-------|
| $N_H$ ($10^{20}$ cm$^{-2}$) | 4 (fixed) |
| $kT_e$ (keV) | 0.23 ± 0.01 |
| O (=C = N) | 0.086 ± 0.002 |
| Ne | 0.17 ± 0.01 |
| Mg | 0.14 ± 0.03 |
| Si | 0.3 ± 0.1 |
| S | 0.6 ± 0.2 |
| Fe (=Ni) | 0.157 ± 0.006 |
| log $\tau$ (cm$^{-3}$ s) | 11.31 ± 0.02 |
| $EM^*$ ($10^{19}$ cm$^{-2}$) | 11.0$^{+1.4}_{-0.5}$ |
| $\chi^2$/dof | 420/314 |

**Note.**—Other elements are fixed to solar values. The abundances are multiples of the solar value. The errors are in the range $\Delta \chi^2 < 2.7$ for one parameter.

$^a$ Emission measure, $\int n_e n_H dl$.

**TABLE 3**

| Parameter | Value |
|-----------|-------|
| $N_H$ ($10^{20}$ cm$^{-2}$) | 4 (fixed) |
| Low-temperature component: $kT_e$ (keV) | 0.20 ± 0.01 |
| C | 0.27 (fixed) |
| N | 0.10 (fixed) |
| O | 0.11 (fixed) |
| Ne | 0.21 (fixed) |
| Mg | 0.17 (fixed) |
| Si | 0.34 (fixed) |
| S | 0.17 (fixed) |
| Fe (=Ni) | 0.20 (fixed) |
| log $\tau$ (cm$^{-3}$ s) | <12 |
| $EM^*$ ($10^{19}$ cm$^{-2}$) | 1.34$^{+0.03}_{-0.04}$ |
| High-temperature component: $kT_e$ (keV) | 0.48 ± 0.01 |
| O (=C = N) | <0.01 |
| Ne | 0.15$^{+0.06}_{-0.07}$ |
| Mg | 0.21 ± 0.08 |
| Si | 2.5 ± 0.3 |
| S | 5 ± 1 |
| Fe (=Ni) | 1.03 ± 0.04 |
| log $\tau$ (cm$^{-3}$ s) | 11.12 ± 0.05 |
| $EM^*$ ($10^{19}$ cm$^{-2}$) | 0.094$^{+0.005}_{-0.004}$ |
| $\chi^2$/dof | 531/377 |

**Note.**—Other elements are fixed to solar values. The abundances are multiples of the solar value. The errors are in the range $\Delta \chi^2 < 2.7$ for one parameter.

$^a$ Emission measure, $\int n_e n_H dl$. 

**Figure 5 (right) and Table 3** show an example result that comes from the sector at $R = +10'$. Fixed parameters in the low-$kT_e$ component come from the fitting result at the northeast rim obtained from Suzaku observations (Uchida et al. 2006). Metal abundances for the high-$kT_e$ component show higher values by an order of magnitude than those of the low-$kT_e$ component, surely confirming that the high-$kT_e$ component is dominated by fossil ejecta.

Figure 6 shows temperatures as a function of position. The low-$kT_e$ component is in the range 0.12–0.34 keV, while the high-$kT_e$ component lies above 0.35 keV. There is a clear temperature
difference where a two-component model is required rather than a single-temperature model. The low-\(kT_e\) component represents the cavity material surrounding the Cygnus Loop, while the high-\(kT_e\) component represents the fossil ejecta inside the Loop. Figure 7 shows the fluxes for the two components as a function of position. The low-\(kT_e\) component shows clear rim brightening. The eastern part is stronger than the western part, demonstrating the asymmetry of the Loop. On the other hand, the high-\(kT_e\) component has a relatively flat radial dependence. From the center to the southwest, one can see that the flux of the high-\(kT_e\) component is stronger than that of the low-\(kT_e\) component.

3.4.1. Distribution of the Cavity Material

As shown in Figure 6, the low-\(kT_e\) component has a relatively constant temperature with radius. The flux distribution in Figure 7 peaks at the rim and exhibits relatively low values inside the Loop. There are some differences between the north path and the south path. The biggest one is a clear difference in peak position in the northeast rim that is due to the bright filament oriented 45° to the radial direction, as seen in Figure 1. However, these two paths exhibit a globally similar behavior in flux. Therefore, we can say that they are quite similar to each other from a large-scale point of view.

We note that there are many aspects showing asymmetry and nonuniformity. The northeast half is stronger in intensity than the southwest half. The flux in the inner part of the Loop has relatively small values in the western half, particularly at \(+25° < R < +40°\). The northeast half is brighter by a factor of \(5 - 10\) than the southwest half. Furthermore, the southwest half shows stronger intensity variations than the northeast half. This suggests that the thickness of the cavity shell is far from uniform. The cavity shell in the southwest half is much thinner than that in the northeast. Since we assumed the metal abundances of the low-\(kT_e\) component to be equal to those of the northeast rim, we can calculate the EM. Furthermore, we assumed an ambient density of \(0.7 \text{ cm}^{-3}\) based on the observation of the northeast rim, and we estimate the mass of the low-\(kT_e\) component to be \(130 M_\odot\). However, we should note that there is evidence that the SN explosion that produced the Cygnus Loop occurred within a preexisting cavity (e.g., Hester et al. 1994; Levenson et al. 1998, 1999). The model predicts that the original cavity density, \(n_c\), is related to the wall density \(n_w\) by \(n_s \neq n_c = 5\). Assuming that \(n_0\) equals the ambient density, \(n_c\), we estimate \(n_c\) to be \(0.14 \text{ cm}^{-3}\). Thus we calculate the total mass in the preexisting cavity to be \(\sim 25 M_\odot\).

3.4.2. Ejecta Distribution

The flux distribution from the ejecta along the path is shown by circles in Figure 7. It has a relatively flat structure, with two troughs around \(R = -35°\) and \(R = +50°\). Since we left the metal abundances as free parameters, we obtained distributions of the EM of various metals (\(C = N = O, \text{Fe} = \text{Ni}, \text{Mg}, \text{Si}, \text{and} S\)) in the ejecta. These are shown in Figure 8, where black circles trace the north path and red circles trace the south path. If we assume uniform plasma conditions along the line of sight, then the EM represents the mass of the metal. Most elements show similar structure between the north and south paths, while there is a significant discrepancy in the Fe/Ni distribution at \(10° < R < +30°\). In this region, the south path is twice as abundant in Fe/Ni as the north path. A similar discrepancy is seen in O (\(-30° < R < -10°\)) and in Ne (at \(-10° < R < +10°\)). Therefore, the distribution of metal abundance shows a north-south asymmetry along the path.

The distributions of O and Ne display a central bump and then increase in the outer sectors. However, those of Mg, Si, S, and Fe only show the central bump. The increase of O and Ne in the south path indicates that the outer parts of the ejecta are well mixed. Similarly, heavy elements, Mg, Si, S, and Fe/Ni, forming central bumps may show that they are well mixed. Therefore, significant convection has occurred in the central bumps, while an “onionskin” structure remains in the outer sectors.

4. DISCUSSION

The Cygnus Loop appears to be almost circular, with a blown-out area in the south. The ROSAT image indicates no clear shell in this blowout region. Levenson et al. (1997) revealed that there is a thin shell left at the edge of the blowout region. Therefore, there is a small amount of cavity material in this region that surrounds the ejecta. This also indicates that the cavity wall is nonuniform. If the cavity wall is thin, the ejecta can produce a blowout structure.

Looking at the component of the cavity material along our path shown in Figure 7, the flux is very weak at \(+15° < R < +40°\). This indicates that the cavity wall is very thin in this region. When we calculate the flux ratio between the ejecta plasma and the cavity material, we find that it becomes high (larger than 4) at
+15\degree < R < +35\degree in the north path and +30\degree < R < +35\degree in the south path. Therefore, we guess that the thin-shell region is larger in the north path than in the south path. This also demonstrates the asymmetry between the north and the south, as well as that between the east and west. If the thin-shell region corresponds to a blowout similar to that in the south, this region must have a blowout structure along the line of sight on the near side, the far side, or both. This structure roughly corresponds to Pos-5 and will extend further to the northwest. Looking at the ROSAT image in Figure 1, one can see a circular region with low intensity. It is centered at 20h49m11s, 31\degree05\arcmin20\arcsec with a radius of 30\arcmin. We guess that this region corresponds to a possible blowout in the direction of our line of sight. CCD observations just north of our path will test this hypothesis.

We obtained EMs of O, Ne, Mg, Si, S, and Fe for the ejecta along the north path and the south path. Multiplying the EMs by the area of each sector, we obtain the emission integral (EI = \int n_e n_{H} dV, where dV is the X-ray-emitting volume) along the path. Since we only observed a limited area of the Cygnus Loop from the northeast rim to the southwest rim, we have to estimate the EIs for the entire remnant in order to obtain the relative abundances, as well as the total mass of the ejecta. Therefore, we...

---

**Figure 8.** Distributions of EM for various metals (O \[\equiv C = N\], Ne, Mg, Si, S, and Fe \[\equiv Ni\]) in the ejecta. Black indicates the north path, and red indicates the south path. Data points showing only upper limits were excluded from these figures.
divided our observation region into four parts: left-north, right-north, left-south, and right-south. We assume that each part represents the average EI of the corresponding quadrant of the Loop. In this way, we can calculate the total EIs for O, Ne, Mg, Si, S, and Fe, which are listed in Table 4. The southern path, corresponding to the right-south quadrant, contains the largest mass fraction, at 31%, while the other quadrants contain 23% each. Then we calculate the abundances of Ne, Mg, Si, S, and Fe relative to O in the whole of the ejecta. Since we cannot measure the abundance of light elements such as He, it is quite difficult to estimate the absolute abundances. However, the relative abundance to O is robust.

Since the Cygnus Loop is believed to have resulted from a core-collapse SN, we compared our data with core-collapse SN models. There are many theoretical results from various authors (e.g., Woosley & Weaver 1995; Thielemann et al. 1996; Rauscher et al. 2002; N. Tominaga et al. 2008, in preparation). We also employed a Type Ia SN model (Iwamoto et al. 1999) for comparison. We calculated the abundances for various elements relative to O and compared them with the models. Figure 9 shows comparisons between the model calculations and our results, where we picked up Woosley’s solar-abundance model (Anders & Grevesse 1989) for the core-collapse case (Woosley & Weaver 1995). The Type Ia model yields more Si, S, and Fe than our results but less Ne. Models with massive stars produce better fits to our results than the Type Ia model. Among them, we found that a model with 15 $M_\odot$ shows good fits to our results. They fit within a factor of 2, with the exception of Fe. We also note that the solar-abundance model produced a better fit than one with depleted abundances. Therefore, we conclude that the Cygnus Loop originated from an approximately 15 $M_\odot$ star with solar abundances.

Assuming that the ejecta density is uniform along the line of sight, we estimate the total mass of the fossil ejecta to be 21 $M_\odot$. In this calculation, we assumed that the electron density is equal to that of hydrogen and that the plasma filling factor is unity, although the fossil ejecta might be deficient in hydrogen. If this is the case, the total mass of the fossil ejecta is reduced to $\sim 12 M_\odot$, whereas the relative abundances are not affected. The most suitable nucleosynthesis model predicts that the total mass ejected is about 6 $M_\odot$ without H. Therefore, there might be a significant amount of contamination from the swept-up matter into the high-$kT_e$ component, which we consider to be the ejecta. Otherwise, the assumption that the density of the ejecta is uniform might be incorrect, since rim brightening for the EMs of O, Ne, Mg, and Fe is clearly seen in Figure 8. Nonuniformity reduces the filling factor and also the mass of the high-$kT_e$ component.

There is observational evidence for the asymmetry of supernova explosions, both for massive stars (Leonard et al. 2006) and for Type Ia SNe (Motohara et al. 2006). We found that the ejecta plasma shows an asymmetric structure between the northeast half and southwest half. Ne and Fe are evenly divided, while two-thirds of the O and Mg are in the northeast half. On the contrary, two-thirds of Si and S are in the southwest half. We calculated the ejecta mass for each quadrant and found that the southern quadrant contains the largest ejecta mass. Similar asymmetries are seen in other SNRs, such as Puppis A, which has an asymmetric structure with O-rich, fast-moving knots (Winkler & Kirscher 1985; Winkler et al. 1988). The central compact object in Puppis A is on the opposite side of the SNR from these knots (Petre et al. 1996). If the asymmetry of the ejecta in the Cygnus Loop is similar to that of Puppis A, we may expect a compact object to lie in the northern direction.

5. CONCLUSION

We have observed the Cygnus Loop along the diameter from the northeast rim to the southwest rim, employing XMM-Newton. The FOV was divided into two paths: the north path and the south path. Then it was further divided into many small annuli so that each annulus contains a similar number of photons, to preserve statistics.

The spectra from the rim regions can be described with a one-temperature model, while those in the inner region require two $kT_e$ components. The low-$kT_e$ plasma shows relatively low metal abundances and covers the entire FOV. It forms a shell that originates from the preexisting cavity. The high-$kT_e$ plasma shows high metal abundances and occupies a large part of the FOV. The origins of these two components are different: the high-$kT_e$ plasma with high metal abundance must come from the ejecta, while the low-$kT_e$ plasma with low metal abundance must come from the cavity material. We find that the thickness of the shell is very thin in the southwest part, where, we guess, the ejecta plasma is blown out in the direction of our line of sight.

We estimated the mass of the metals. Based on the relative metal abundances, we find that the Cygnus Loop originated from a 15 $M_\odot$ star. The distribution of the ejecta is asymmetric, suggesting an asymmetric explosion.

This work was partly supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology of Japan (No. 16002004). This study was also carried out as part of the 21st Century Center of Excellence Program “Towards a New Basic Science: Depth and Synthesis.” S. K. is supported by a Research Fellowship for Young Scientists from the Japan Society for the Promotion of Science.
REFERENCES

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco: ASP), 17
Aschenbach, B., & Leahy, D. A. 1999, A&A, 341, 602
Blair, W. P., Sankrit, R., & Raymond, J. C. 2005, AJ, 129, 2268
Borkowski, K. J., Lyerly, W. J., & Reynolds, S. P. 2001, ApJ, 548, 820
Cartledge, S. I. B., Lauroesch, J. T., Meyer, D. M., & Sofia, U. J. 2004, ApJ, 613, 1037
Dopita, M. A., Mathewson, D. S., & Ford, V. L. 1977, ApJ, 214, 179
Fujita, Y., Sarazin, C. L., Reiprich, T. H., Andernach, H., Ehle, M., Murgia, M., Rudnich, L., & Slee, O. B. 2004, ApJ, 616, 157
Hatsukade, I., & Tsunemi, H. 1990, ApJ, 362, 566
Hester, J. J., Raymond, J. C., & Blair, W. P. 1994, ApJ, 420, 721
Inoue, H., Koyama, K., Matsuoka, M., Ohashi, T., Tanaka, Y., & Tsunemi, H. 1980, ApJ, 238, 886
Iwamoto, K., Brachwitz, F., Nomoto, K., Kishimoto, N., Umeda, H., Hix, W. R., & Thielemann, F.-K. 1999, ApJS, 125, 439
Kahn, S. M., Charles, P. A., Bowyer, S., & Blissett, R. J. 1980, ApJ, 242, L19
Katsuda, S., Tsunemi, H., Uchida, H., Miyata, E., Nemes, N., Miller, E. D., & Hughes, J. P. 2008, PASJ, in press
Kirsch, M. 2006, EPIC Status of Calibration and Data Analysis (XMM-SOC-CAL-TN-0018) (issue 2.5; Madrid: European Space Astron. Cent.)
Leahy, D. A. 2004, MNRAS, 351, 385
Leonard, D. C., et al. 2006, Nature, 440, 505
Levenson, N. A., Graham, J. R., Keller, L. D., & Richter, M. J. 1998, ApJS, 118, 541
Levenson, N. A., Graham, J. R., & Snowden, S. L. 1999, ApJ, 526, 874
Levenson, N. A., et al. 1997, ApJ, 484, 304
McCray, R., & Snow, T. P., Jr. 1979, ARA&A, 17, 213
Minkowski, R. 1958, Rev. Mod. Phys., 30, 1048
Mitsuda, K., et al. 2007, PASJ, 59, S1
Miyata, E., Katsuda, S., Tsunemi, H., Hughes, J. P., Kokubun, M., & Porter, F. S. 2007, PASJ, 59, S163
Miyata, E., & Tsunemi, H. 1999, ApJ, 525, 305
Miyata, E., Tsunemi, H., Kohmura, T., Suzuki, S., & Kurnagai, S. 1998, PASJ, 50, 257
Miyata, E., Tsunemi, H., Pisarki, R., & Kissel, S. E. 1994, PASJ, 46, L101
Morrison, R., & McCammon, D. 1983, ApJ, 270, 119
Motohara, K., et al. 2006, ApJ, 652, L101
Nevalainen, J., Lieu, R., Bonamente, M., & Lumb, D. 2003, ApJ, 584, 716
Petre, R., Becker, C. M., & Winkler, P. F. 1996, ApJ, 465, L43
Rauscher, T., Heger, A., Hoffinan, R. D., & Woosley, S. E. 2002, ApJ, 576, 323
Read, A. M., & Pomran, T. J. 2003, A&A, 409, 395
Sato, K., Furusho, T., Yamasaki, Y., Ishida, M., Matsushida, K., & Ohashi, T. 2005, PASJ, 57, 743
Thielemann, F.-K., Nomoto, K., & Hashimoto, M. 1996, ApJ, 460, 408
Uchida, H., Katsuda, S., Miyata, E., Tsunemi, H., Hughes, J. P., Kokubun, M., & Porter, F. S. 2006, Poster at The Extreme Universe in the Suzaku Era (Kyoto) (abstr. booklet, No. 81)
Wilms, J., Allen, A., & McCray, R. 2000, ApJ, 542, 914
Winkler, P. F., & Kirshner, R. P. 1985, ApJ, 299, 981
Winkler, P. F., Tuttle, J. H., Kirshner, R. P., & Irwin, M. J. 1988, in IAU Colloq. 101, Supernova Remnants and the Interstellar Medium, ed. R. S. Roger & T. L. Landecker (Cambridge: Cambridge Univ. Press), 65
Woosley, S. E., & Weaver, T. A. 1995, ApJS, 101, 181

PLASMA STRUCTURE OF CYGNUS LOOP 1725

No. 2, 2007