THE PLASMA STRUCTURE OF THE SOUTHWESTERN REGION OF THE CYGNUS LOOP WITH THE XMM-NEWTON OBSERVATORY

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ABSTRACT

We observed the southwestern region of the Cygnus Loop in two pointings with XMM-Newton. The region observed is called the “blow-out” region, which is extended further in the south. The origin of the “blow out” is not well understood, but it is suggested that there is another supernova remnant here in radio observation. To investigate in detail the structure of this region in X-ray, we divided our fields of view into 33 box regions. The spectra are well fitted by a two-component nonequilibrium ionization model. The emission measure distributions of heavy elements decrease from the inner region to the outer region of the Loop. Then, we also divided our fields of view into 26 annular sectors to examine the radial plasma structure. Judging from the metal abundances obtained, it is consistent that the X-ray emission is of Cygnus Loop origin, and we conclude that the high-\(kT_e\) component (\(\sim 0.4\) keV) originates from the ejecta, while the low-\(kT_e\) component (\(\sim 0.2\) keV) is derived from the swept-up interstellar medium. The flux of the low-\(kT_e\) component is much less than that of high-\(kT_e\) component, suggesting that the ISM component is very thin. Also, the relative abundances in the ejecta component show values similar to those obtained from previous observations of the Cygnus Loop. We find no evidence in X-ray that the nature of the “blow-out” region originated from the extra supernova remnant. From the ejecta component, we calculated the masses for various metals and estimated the origin of the Cygnus Loop as a core-collapse explosion rather than a Type Ia supernova.

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

1. INTRODUCTION

The Cygnus Loop is one of the brightest supernova remnants (SNRs) in the X-ray sky. Its age is estimated to be \(\sim 10,000\) yr old (Blair et al. 2005). Since it is comparatively close to us (540 pc; Blair et al. 2005), the apparent size is quite large (2.5° \(\times\) 3.5°; Levenson et al. 1997), which enables us to study the plasma structure of the Loop in detail.

Although the Cygnus Loop is an evolved SNR, a hot plasma is still confined inside the Loop (Hatsukade & Tsunemi 1990). Miyata & Tsunemi (1999) observed the Loop with the Advanced Satellite for Cosmology and Astrophysics (ASCA), and detected strong, highly ionized Si K, S K, and Fe L lines near the center of the Cygnus Loop. They concluded that there is a hot plasma, a “fossil” of the supernova explosion, left in the core of the Loop. Tsunemi et al. (2007, hereafter TKNM07) observed the Cygnus Loop along the diameter from the northeast to the southwest with XMM-Newton and studied the radial plasma structure. From the spectral analysis, they showed that the Cygnus Loop consists of two component plasmas. They concluded that a low-\(kT_e\) component originating from the interstellar medium (ISM) surrounds a high-\(kT_e\) component originating from the ejecta. In addition, they measured the metal abundances of the high-\(kT_e\) component and showed the metal distribution of the ejecta. The results indicate that the abundances are relatively high (\(\sim 5\) times solar) and each element is nonuniformly distributed: Si, S, and Fe are concentrated in the inner region, while the other elements, such as O, Ne, and Mg, are abundant in the outer region. They also estimated the progenitor star’s mass to be 15\(M_\odot\).

The Cygnus Loop is a typical shell-like SNR; this structure is thought to be generated by a cavity explosion (Levenson et al. 1997). The Cygnus Loop is almost circular in shape; however, we can see some breakout in the southwest. This is called the “blow-out” region (Aschenbach & Leahy 1999). The origin of the “blow-out” is not well understood. Aschenbach & Leahy (1999) have explained this extended structure as a breakout into a lower density ISM. On the other hand, Uyaniker et al. (2002) suggested the existence of a secondary SNR (named G72.9-9.0) in the south from a radio observation, and some other radio observations support this conclusion (Uyaniker et al. 2004; Sun et al. 2006).

Our observations were performed in a direction from the Cygnus Loop center toward the south “blow-out” region. In this paper, we report the result of the spectral analysis and discuss the plasma structure of this region.

2. OBSERVATIONS

We performed two pointing observations of the southwestern region of the Cygnus Loop with the XMM-Newton observatory. TKNM07 have observed from the northeast to the southwest along the diameter. Then, we intended to expand our observation southward from the center. Figure 1 (left) shows the X-ray surface brightness map of the Cygnus Loop obtained with ROSAT High Resolution Imager (HRI). The figure shows the field of view (FOV) of the EPIC MOS by solid white circles. We call the north observation Position-8 (Pos-8) and the south observation Position-9 (Pos-9). If there exists a secondary SNR in southwest as Uyaniker et al. mentioned, our whole FOV overlaps the SNR, whose center is roughly located at the south in Pos-9. Figure 1 (right) shows a three-color X-ray image of our FOV using XMM-Newton EPIC MOS 1 and 2 data after correcting for exposure and vignetting effects. Red, green, and blue correspond to the energy ranges of 0.3–0.5, 0.5–0.7, and 0.7–3.0 keV, respectively. Figure 2 shows the MOS broadband image for the 0.3–3 keV range. The white cross shows the center of the G72.9-9.0 estimated by Uyaniker et al. (2002).
Both observations were performed on 2006 May 13, during the XMM-Newton AO-5 observing cycle. The total exposure time was both ~10 ks. In order to exclude the background flare events, we considered the time intervals in which the count rates were high as flare events and eliminated them from our analysis. The pn data were almost unusable due to the flare. Therefore, we used only the data obtained with the EPIC MOS for our analysis. The effective exposure times for each observation were 6.5 ks (Pos-8) and 3.6 ks (Pos-9), respectively. Both data were taken using the medium filters and the prime full-window mode. All the data were processed with version 7.1.0 of the XMM Science Analysis System (SAS). For the background subtraction, we employed blank-sky observations prepared by Read & Ponman (2003). Pointlike sources were excluded using the SAS task edetect chain for the spectral analysis. As a result, one and four point-like sources are detected in Pos-8 and Pos-9, respectively. Two of the point sources in Pos-9 were observed by Miyata et al. (2001) and named AX J2049.6+2939 and AX J2050.0+2914, respectively.

3. SPECTRAL ANALYSIS

3.1. Two-Component VNEI Model

Figure 3 shows the spectra for Pos-8 and Pos-9 summed over the entire FOV. We can see some emission lines, such as O Heα, O Lyα, the Fe L complex, Ne Heα, Mg Heα, and Si Heα, while the S line is not seen here.

First, we fitted each spectrum by a single-component nonequilibrium ionization (VNEI) model. We employed wabs (Morrison & McCammon 1983) and vnei (NEI ver.2.0; Borkowski et al. 2001) in XSPEC version 12.3.1 (Arnaud 1996). In the model, the abundances of O, Ne, Mg, Si, and Fe were free, while we set the abundances of C and N equal to O, S equal to Si, Ni equal to Fe, and other elements to their solar values (Anders & Grevesse 1989). Other parameters were all free, such as the electron temperature $kT_e$, the ionization timescale $\tau$ (a product of the electron density and the elapsed time after the shock heating), and the emission measure ($EM = \int n_e n_H dl$, where $n_e$ and $n_H$ are the number densities of hydrogen and electrons and $dl$ is the plasma depth). We also set the column density $N_H$ free. From the best-fit parameters, we found that the value of $kT_e$ (~0.4 keV) is higher than that of the result at the northeast rim obtained from Suzaku observations (~0.2 keV; Katsuda et al. 2008b). Also, the metal abundances, such as Si (~1.0) and Fe (~0.4), show values about 2 times higher than those of the northeast rim. These facts suggest that the X-ray emission in Pos-8 and Pos-9 mainly consists of a high-$kT_e$ component, which was explained by $x^1$. However, the values of reduced $\chi^2$ are 6.9 and 3.6 in Pos-8 and Pos-9, respectively. The model is too simple to sufficiently fit the data. Therefore, we added the extra component to the VNEI model.

From the standpoint of the SNR’s evolution, the X-ray emission from the SNRs has the two different origins. The blast wave from the supernova explosion sweeps the ambient medium, while the reverse shock propagates into the ejecta. Each shock wave heats up the swept-up ISM and the ejecta, respectively. The shock-ISM interaction also produces a reflected shock, which moves back through the previously swept-up ISM (Hester et al. 1994). Because of this, the X-ray spectra of AN evolved SNR such as the Cygnus Loop should have a complicated structure. From the earlier observations of the northeast to the southwest regions, TKNM07 proposed the plasma structure of the Cygnus Loop to be as follows: a high-$kT_e$ ejecta component is surrounded by a low-$kT_e$ ISM component. They found that the spectra from most regions of the Cygnus Loop consist of the two-component VNEI model. Thus we also employed a two-component VNEI model which has two different electron temperatures. We found that this model cannot reach physically meaningful results by setting all the parameters free. Therefore, in the low-$kT_e$ component, we fixed the metal abundances to the values from the northeast rim observations (Uchida et al. 2006). Other parameters, such as
Fig. 2.—Left: *XMM-Newton* MOS broadband image for the 0.3–3 keV range. White lines represent the spectral extraction regions. The green circles show the pointlike source regions excluded from our spectral analysis. The white X shows the center of the G72.9-9.0 estimated by Uyaniker et al. (2002) Right: Same as the left panel, but for the different spectral extraction regions.

Fig. 3.—Left: MOS 1 (black) and MOS 2 (red) spectrum for Pos-8, which are summed over the entire FOV. The best-fit curves are shown as solid lines. The dotted lines show individual component of the model. The lower panel shows the residual. Right: Same as the left panel, but for Pos-9.
Fig. 4.—Maps of the best-fit parameters. EM$_H$ and EM$_L$ mean the emission measure of the high- and low-$kT_e$ components, respectively. The last five panels show the EMs of O ($\equiv$C=N), Ne, Mg ($\equiv$S), and Fe ($\equiv$Ni) for the high-$kT_e$ component in units of $10^{14}$ cm$^{-5}$. The values of $kT_e$ and EM$_{H,L}$ are in units of keV and $10^{18}$ cm$^{-5}$, respectively.
Each lower panel shows the residual. The dotted lines of the right panel show individual component of the two-kT_e constant-temperature, plane-parallel shock plasma model regions for the spectral analysis. Although we employed the is a lot of structure. Therefore, we divided our FOV into several we took the spectra summed over the entire FOV in which there remain almost unchanged: 6.9
kT_e
and the values of the reduced \( \chi^2/C_{31} \) in the above paragraph. As a result, the values of the reduced \( \chi^2/C_{31} \) were not significantly improved.

### 3.2. Spatially Resolved Spectral Analysis

From Figure 2 we can see several structures within Pos-8 and Pos-9. For example, there is a region of high surface brightness at the center of both Pos-8 and Pos-9, even after correcting the vignetting effect. We notice that they are different in color in Figure 1 (right), which shows that the plasma temperatures from each region are different. In order to investigate the plasma structure in detail, we divided our FOV into a number of box regions for the spectral analysis. To equalize the statistics, we determined the box sizes such that each region has 7500–15,000 photons for MOS 1 and 2. In this way, we have 33 regions (22 and 11 regions in Pos-8 and Pos-9, respectively). Figure 2 (left) shows the XMM-Newton MOS broad band image for the 0.3–3.0 keV range and box regions are shown in white lines.

To examine the plasma structure of Pos-8 and Pos-9, we fitted 33 spectra extracted from box regions by the single-kT_e VNEI model and two-kT_e VNEI model, respectively. In the two-kT_e VNEI model, we fixed the metal abundances of the low-kT_e component to the result from the observations of the northeast rim, as explained in § 3.1. As in the case of the fit for each whole region, the values of the reduced \( \chi^2 \) are improved from \(~1.6\) to \(~1.3\) and \(~1.4\) to \(~1.1\) in Pos-8 and Pos-9, respectively. The \( F \)-test probability (>99\%) shows that it is reasonable to add the extra low-kT_e VNEI model in more than half of the regions. The best-fit parameters are mapped in Figure 4. The averaged temperatures of high- and low-kT_e components are \(~0.4\) and \(~0.2\) keV, respectively. However, the low-kT_e temperatures are determined only as an upper limit in several regions where the contribution of the low-kT_e component is quite low, as shown in the EM_L map in Figure 4.

We compared these parameters and EMs of heavy elements with the results of Katsuda et al. (2008a). They observed the Cygnus Loop in seven pointings from the northeast to the southwest with Suzaku and showed the best-fit parameters using the two-kT_e VNEI model. One of their observation regions (named P16) is next to the northeast part of Pos-8 (see Fig. 1). From the results of P16 observations, the temperatures of the high- and low-kT_e components are \(~0.4\) and \(~0.2\) keV, respectively. These values are similar to our results. Katsuda et al. concluded that the emission of the high-kT_e component comes from the ejecta of the Cygnus Loop. Then we compared the EMs of O (=C=N), Ne, Mg, Si (=S), and Fe (=Ni) between in P16 and our FOV, as shown in Table 1. Katsuda et al. (2008a) showed that each EM in their FOV reduces from the center to the outer region of the Loop. From Table 1, we found that this trend is also seen from P16 to our FOV.

Then, we determined the spectral extraction regions in different way to investigate the plasma structure from the inner side of the Loop to the outside.

We divided our FOV into two paths: an east path and a west path. Then we divided several annular sectors as shown in Figure 2 (right). To compare our analysis with that of TKNM07, we set the annular center on 20h51m34.7s, 31°00′00″ (J2000.0). In order to equalize the statistics, we determined the annular widths such that each sector has at least \(~10,000 \pm 1,000\) photons. In this way, we have 26 annular sectors (16 and 10 sectors in the east and the west paths, respectively) whose angular distances from the center are from 35′ to 95′. The width ranges from 1′ to 6.5′.

Figure 5 shows an example of the spectrum from the sector at \( R = 42.5′ \), where \( R \) represents the angular distance from the

| TABLE 1 |
| --- |
| **Comparison between the Averaged EM for Each Element in our FOV and P16 (Katsuda et al. 2008a)** |
| **EM of Each Element** | \( 10^{14} \text{ cm}^{-2} \) | P16 | Pos-8 | Pos-9 |
| O(=C=N) | 4.2 | 1.2 | 0.28 |
| Ne | 0.42 | 0.25 | 0.09 |
| Mg | 0.04 | 0.02 | 0.01 |
| Si | 1.7 | 0.54 | 0.22 |
| Fe(=Ni) | 1.1 | 0.41 | 0.12 |
| Si (=S) | 1.7 | 0.54 | 0.22 |
| Mg | 1.1 | 0.41 | 0.12 |

Fig. 5.—Example spectra at \( R = 42.5′ \). The solid line of each panel shows the best-fit curve with the single-kT_e VNEI model and the two-kT_e VNEI model, respectively. Each lower panel shows the residual. The dotted lines of the right panel show individual component of the two-kT_e VNEI model.
center. The left and right panels show the best-fit curves with the single- and the two-\(kT_e\) VNEI models, respectively. The fitting parameters are set as explained in §3.1. Dotted lines in Figure 5 represent the individual model. From Figure 5 (right), we found that the contribution of the low-\(kT_e\) component is lower than that of the high-\(kT_e\) component.

The best-fit parameters are shown in Tables 2 and 3, respectively. The \(F\)-test probability (99%) shows that it is reasonable to add the extra low-\(kT_e\) VNEI model in this sector.

Then, we analyzed all other sectors in the same way. Figure 6 shows the radial plot of the values of \(\chi^2\) along the east path (top) and the west path (bottom). The single-\(kT_e\) VNEI model is shown in black, while the two-\(kT_e\) VNEI model is shown in red. From the results, we calculated the \(F\)-test probability and determined whether or not the extra component is needed for each sector. Applying the significance level of 99%, the extra component is not required at 47.5\(\prime\) < \(R\) < 75.0\(\prime\) and 77.5\(\prime\) < \(R\) < 95.0\(\prime\) along the east path, and 36.0\(\prime\) < \(R\) < 43.0\(\prime\), 47.0\(\prime\) < \(R\) < 65.0\(\prime\), and 85.0\(\prime\) < \(R\) < 95.0\(\prime\) along the west path. In other words, \sim 60\% of our FOV requires the two-\(kT_e\) VNEI model. We find that the fit shown in Figure 5 (at \(R\) = 42.5\(\prime\)) is improved the most by using the two-\(kT_e\) VNEI model. Even in this sector, the contribution of the additional low-\(kT_e\) component is not so large.

**4. DISCUSSION**

The first two panels of Figure 4 show the temperature distributions of the two components based on the analysis in Figure 2 (left). Figure 7 shows the temperature distributions along the east path (top) and the west path (bottom) based on the analysis in Figure 2 (right). Black and red represent the low-\(kT_e\) and the high-\(kT_e\) temperatures, respectively. From Figures 4 and 7, the averaged

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**TABLE 2**

**Spectral Fit Parameters**

| Parameter | Pos-8 |
|-----------|-------|
| \(N_H (10^{20} \text{ cm}^{-2})\) | \(4 \pm 1\) |
| \(kT_e (\text{keV})\) | \(0.46 \pm 0.02\) |
| \(\text{O}(=\text{C}=\text{N})\) | \(0.04 \pm 0.01\) |
| \(\text{Ne}\) | \(0.09 \pm 0.01\) |
| \(\text{Mg}\) | \(0.04 \pm 0.02\) |
| \(\text{Si}\) | \(0.79 \pm 0.16\) |
| \(\text{Fe}(\text{Ni})\) | \(0.33 \pm 0.03\) |
| \(\log \tau\) | \(10.58\) |
| \(EM^* (10^{18} \text{ cm}^{-3})\) | \(2.54 \pm 0.56\) |
| \(\chi^2/\text{dof}\) | \(187/133\) |

Notes.— Other elements are fixed to solar values. The errors are in the range \(\Delta \chi^2 < 2.7\) for one parameter.

**TABLE 3**

**Spectral Fit Parameters**

| Parameter | Value |
|-----------|-------|
| \(N_H (10^{20} \text{ cm}^{-2})\) | \(<4\) |
| Low-\(kT_e\) component: | | |
| \(kT_e (\text{keV})\) | \(0.26 \pm 0.07\) |
| \(\text{C}\) | \(0.27\) (fixed) |
| \(\text{N}\) | \(0.10\) (fixed) |
| \(\text{O}\) | \(0.11\) (fixed) |
| \(\text{Ne}\) | \(0.21\) (fixed) |
| \(\text{Mg}\) | \(0.17\) (fixed) |
| \(\text{Si}\) | \(0.34\) (fixed) |
| \(\text{S}\) | \(0.17\) (fixed) |
| \(\text{Fe}(\text{Ni})\) | \(0.20\) (fixed) |
| \(\log \tau\) | \(10.62\) |
| \(EM^* (10^{18} \text{ cm}^{-3})\) | \(<0.57\) |
| High-\(kT_e\) component: | | |
| \(kT_e (\text{keV})\) | \(0.47 \pm 0.02\) |
| \(\text{O}(=\text{C}=\text{N})\) | \(0.06 \pm 0.02\) |
| \(\text{Ne}\) | \(0.08 \pm 0.03\) |
| \(\text{Mg}\) | \(0.06 \pm 0.03\) |
| \(\text{Si}\) | \(0.65 \pm 0.14\) |
| \(\text{Fe}(\text{Ni})\) | \(0.42 \pm 0.05\) |
| \(\log \tau\) | \(11.29 \pm 0.03\) |
| \(EM^* (10^{18} \text{ cm}^{-3})\) | \(1.88 \pm 0.38\) |
| \(\chi^2/\text{dof}\) | \(167/130\) |

Notes.— Other elements are fixed to solar values. The errors are in the range \(\Delta \chi^2 < 2.7\) for one parameter.

\* Emission measure, \(\int n_e n_H dl\).
values of low- and high-\(kT_e\) temperature are \(\sim 0.2\) and \(\sim 0.4\) keV, respectively. In this way, we clearly separated the high-\(kT_e\) component and the low-\(kT_e\) component just as the observation obtained in Katsuda et al. (2008a) and TKNM07. TKNM07 showed the temperature of the low-\(kT_e\) component is almost constant (\(\sim 0.2\) keV) along the diameter, while that of the high-\(kT_e\) component is different in northeast (\(\sim 0.6\) keV) and southwest (\(\sim 0.4\) keV). Since our FOV is very close to southwest, our result shows smooth extrapolation from that of TKNM07 in southwest rather than that in northeast.

The third and fourth panels of Figure 4 shows the EM distributions for each component. Although there are some structures seen in the EM of the high-\(kT_e\) component (EM\(_{H}\)) map, it is clear that the EM\(_{H}\) is higher in Pos-8 than that in Pos-9. The EM of the low \(kT_e\) component (EM\(_L\)) in all of our FOV are lower than those of EM\(_H\). Figure 8 shows the radial profile of the EMs for each component. In this figure, we calculated the EMs as a function of \(R\) into 10\(^{\prime}\) bin. The EM\(_L\) stays almost constant while it peaks around \(R = 80\)\(^{\prime}\). From the morphological point of view, the Cygnus Loop has an almost circular shape, with a radius \(\sim 80\)\(^{\prime}\) except for the south “blow out.” Then, it is suggested that the EM\(_L\) distribution reflects the rim brightening structure around the “blow-out” region. On the other hand, the value of EM\(_H\) gradually decreases from the center to the outer region. This decrease can be easily explained by assuming that the emission comes from the ejecta component filling inside the Cygnus Loop. Then we also measured the EMs of various heavy elements in the high-\(kT_e\) component such as \(O (=C=N)\), Ne, Mg, Si (=S), and Fe (=Ni), and compared them with the result of TKNM07. Figure 9 shows the EM distribution for these elements as a function of \(R\). We also plot the results of Pos-2 to Pos-6 (TKNM07) in the same panels. Although some structures are remaining in the annular regions as seen in Figure 2, the radial distribution of each EM clearly shows the smooth extrapolation of TKNM07’s result. They showed the decrease of each EM from the center to the outer region and concluded that the high-\(kT_e\) component is derived from the Cygnus Loop ejecta. It is reasonable to understand that the EMs in Pos-8 and Pos-9 show a smooth connection to those in their FOV. Therefore, we concluded that the high-\(kT_e\) component originates from the ejecta of the Cygnus Loop.

From the fitting parameters of the high-\(kT_e\) component, we calculated the abundances of ejecta component for various elements. Figure 10 shows the abundance ratios of heavy elements (Ne, black; Mg, red; Si (=S), green, Fe (=Ni), red) relative to O. From Figure 10, we found that Si/O (\(\sim 20\)) and Fe/O (\(\sim 10\)) are heavily overabundant and Ne/O is \(\sim 2\), while Mg/O (< 1) is depleted. This tendency is kept throughout our observing region. The other observations of the ejecta in the Loop such as TKNM07 and Katsuda et al. (2008a) showed the similar results.

Uyaniker et al. (2002) and Sun et al. (2006) reported that the Cygnus Loop consists of two SNRs interacting with each other in the southwest. Their main arguments are the difference of the radio morphology and the polarization intensity between the main part of the Cygnus Loop and the south “blow-out” region. However, based on the X-ray data, we found that there is no evidence of an extra SNR within our FOV. If these SNRs are at the same distance, as claimed by Uyaniker et al. (2002) and Sun et al. (2006), then the fact that the radius of the extra SNR, \(\sim 7\) pc (\(R/3p c\)), is smaller than that of the Cygnus Loop, \(\sim 13\) pc (\(R/3p c\)), strongly suggests that the extra SNR is younger than the Cygnus Loop is. If we employ the Sedov-Taylor solution, the temperature \(T\) of the extra SNR is

\[
T \sim 1.8 \text{keV} \left( \frac{E_0}{10^{51} \text{ergs}} \right) \left( \frac{n}{1 \text{cm}^{-3}} \right)^{-1} \left( \frac{R}{3 \text{pc}} \right)^{-3},
\]

where \(E_0\) and \(n\) are the explosion energy and the surrounding medium density of the extra SNR, respectively. Therefore, the temperature of the extra SNR should be significantly higher than that of the Cygnus Loop. However, we found no sign of such a high-temperature plasma. The spectra from all regions are almost represented by a single-\(kT_e\) VNEI model (\(\sim 0.4\) keV). When we added an extra component, we found in § 3 that the extra component shows low temperature rather than high temperature. Furthermore, from Figure 7, the temperatures of each component are in good agreement with those obtained in other regions of the Loop (TKNM07; Katsuda et al. 2008a). This result suggests that the X-ray emission from the southwest region mainly comes from the Cygnus Loop. If the secondary SNR exists in the southwest at the same distance, the contribution of the X-ray emission to the spectra is much less than that of the Cygnus Loop. We cannot rule out the possibility that the extra SNR exists far side of the Cygnus Loop. However, even if that is the case, the fact remains that the spectrum from our FOV mainly consists of the ejecta and
Fig. 9.—EM distributions for various metals (O [=C=N], Ne, Mg, Si [=S], and Fe [=Ni]) in the ejecta. Black and red show the west path and east path, respectively. Green shows the result of TKNM07 taken from Pos-2 to Pos-6.
the ISM components of the Cygnus Loop. As a result, we find no evidence in X-ray that there exists the second SNR at the same distance to the Cygnus Loop.

Then, we can estimate the mass of the progenitor star of the Cygnus Loop from the EMs of the high-$kT_e$ component, assuming that all these emissions come from the Loop. Then, we multiplied the EMs by the area of each annular sector and integrated the EMs along the path. In this way, we obtained the emission integral ($EI = \int n_e n_X dV$, where $dV$ is the X-ray-emitting volume) for O, Ne, Mg, Si, and Fe. Table 4 shows the calculated $EI$ of each element. To compare our data with the supernova explosion models, we calculated the ratios of Ne, Mg, Si, and Fe relative to O. Figure 11 shows the number ratios of Ne, Mg, Si, and Fe relative to O of the ejecta component. We also plotted the result from TKNM07, the core-collapse models (Woosley & Weaver 1995) for various progenitor masses and Type Ia supernova models of Iwamoto et al. (1999). The dotted blue, light blue, magenta, and green lines represent core-collapse models with progenitor masses of 12, 13, 15, 20 $M_\odot$, respectively (Woosley & Weaver 1995).

The EM distribution of the low-$kT_e$ component suggests the rim brightening structure, while that of the high-$kT_e$ component monotonously decreases from the center of the Loop to the outside. In the high-$kT_e$ component, the abundances of Si and Fe are relatively high compared to those of Ne and Mg. The distributions of EMs as well as the relative abundances in the high-$kT_e$ component match the view that the low- and high-$kT_e$ components, respectively, originate from the ISM and the ejecta of the Cygnus Loop, which was derived by earlier observations such as TKNM07 or Katsuda et al. (2008a). We found that the emission from this ISM component is relatively weak. This suggests that the thickness of the shell is thin in Pos-8 and 9. We also calculated the relative abundances of Ne, Mg, Si, and Fe to O in the ejecta component for the entire FOV, and estimated the origin of the Cygnus Loop as the core-collapse explosion rather than the Type Ia supernova. We found no evidence in X-ray that the nature of the “blow-out” region originated from the extra SNR.

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