Another Abundance Inhomogeneity in the South East Limb of the Cygnus Loop

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Abstract

We observed the south east (SE) limb of the Cygnus Loop with Suzaku. Our spatially-resolved spectroscopic study shows that a one-\(kT\) non-equilibrium ionization model represents our spectra fairly well. We find that the metal abundances obtained are all depleted relative to the solar values with a positional dependence along the radial direction of the Cygnus Loop. The abundances in the very edge of the limb show about half the solar value, whereas other regions inside the Loop show about 0.2-times the solar value, which has been believed to be a typical value for the Cygnus Loop limb. The “enhanced” abundance in the very edge of the SE limb is quite similar to that found in the north-east (NE) limb of the Loop, and thus this is another evidence of an abundance inhomogeneity in the limb regions of the Loop. The radio map shows a quite different feature: the NE limb is in the radio bright region, while the SE limb shows almost no radio. Therefore, the metal abundance variation in the SE limb can not be attributed to non-thermal emission. The abundance inhomogeneity as well as the metal depletion down to 0.2 times the solar value still remain an open question.

Key words: ISM: abundances — ISM: individual (Cygnus Loop) — ISM: supernova remnants — X-rays: ISM

1. Introduction

The Cygnus Loop is one of the brightest sources below 1 keV. It is a nearby (540 pc: Blair et al. 2005) proto-typical middle-aged (~10000 yr) supernova remnant (SNR) located near the galactic plane: \((l, b) = (74^\circ, -8.5^\circ)\). The foreground neutral hydrogen column density, \(N_H\), is estimated to be \(\approx 4 \times 10^{20}\) cm\(^{-2}\) (Inoue et al. 1979; Kahn et al. 1980). The low foreground absorbing material as well as the large apparent size (2.5 x 3.5: Levenson et al. 1997; Aschenbach & Leahy 1999) and high surface brightness enable us to perform a detailed study of the soft X-ray emission from the Cygnus Loop.

The supernova (SN) explosion of the Cygnus Loop is generally considered to have occurred in a preexisting cavity (firstly noted by McCray & Snow 1979). The X-ray boundary in the northeastern (NE) limb of the Cygnus Loop is associated with Balmer-dominated filaments, which marks current locations of the blast wave (Chevalier & Raymond 1978). Hester et al. (1994) studied a Balmer-dominated filament in detail, and reported that it was recently (in past 100 years) decelerated from \(\approx 400\) to \(\approx 180\) km s\(^{-1}\). This rapid deceleration of the shock velocity was considered to be the result of a blast wave hitting the wall of a cavity surrounding the supernova precursor. Levenson et al. (1999) observed the whole remnant by ROSAT PSPC, and generated a softness map. They found a soft spatially thin (<5’) shell around almost the entire limb of the Loop. Based on the observation, they concluded that the soft shell occurred where the cavity walls of the Cygnus Loop decelerated the blast wave.

An ASCA observation of the NE limb of the Cygnus Loop revealed the non-equilibrium ionization (NEI) plasma condition as well as the depleted metal abundances relative to the solar values by a factor of ~5 (Miyata et al. 1994, 1998). The low metal abundances led them to consider that the plasma in the NE-limb of the Cygnus Loop originated from the swept-up interstellar medium (ISM), rather than the ejecta-material. Recently, Miyata et al. (2007) observed the same region by Suzaku (Mitsuda et al. 2007) Science Working Group (SWG) time program that enabled us to observe emission lines from highly ionized C and N for the first time, and obtained depleted abundances: C ~ 0.1, N ~ 0.03, O ~ 0.1, Ne ~ 0.1, Mg ~ 0.2, Si ~ 0.4, and Fe ~ 0.2. They confirmed the metal deficiency as well as the NEI condition there. Leahy (2004) observed the southwestern (SW) limb of the Cygnus Loop by the Chandra satellite, and performed spatially resolved spectral analysis. In his spectral analysis, he divided the elements into three groups: O-group, Ne-group, and Fe-group. He found the collisional ionization equilibrium (CIE) condition and deficient metal abundances (mean O abundance is 0.22). Levenson and Graham (2005) observed the southeastern (SE) region where a complicated intensity structure is seen. They found the metal abundance to be 0.3–0.6 with the collisional ionization equilibrium condition. Therefore, the low metal abundances may be a common feature, except for the SE region of the Cygnus Loop.

Cartledge et al. (2004) measured the interstellar oxygen along 36 sight lines, and confirmed the homogeneity of the O/H ratio within 800 pc of the Sun. We found that the closest
sight line to the Cygnus Loop was about 5° away. The oxygen abundance they measured was 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 suggest that this depletion may be due to grains. Although the ISM near the Cygnus Loop may be depleted by a factor of 2 compared with the solar values, the abundances are still much higher than that reported at the limb 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 not yet answered.

Recently, Katsuda et al. (2008a) found that the northern outermost region in the NE limb of the Cygnus Loop showed enhanced abundances: C $\sim$ 0.7, N $\sim$ 0.7, O $\sim$ 0.4, Ne $\sim$ 0.6, Mg $\sim$ 0.3, and Fe $\sim$ 0.3 times the solar values. The abundance enhanced region is about a 30' $\times$ 3' region with a relatively weak surface brightness. This is the outermost region of the Loop. The inner part of it showed a depleted abundance. Katsuda et al. (2008b) also confirmed it by Chandra. Based on a study of the plasma structure, they concluded that neither a circumstellar medium, fragments of ejecta, nor abundance inhomogeneities of the local interstellar medium around the Cygnus Loop can explain the relatively enhanced abundance in the region. The apparent abundance in the metal-enhanced region of the NE limb of the Cygnus Loop can be understood as being the average metal abundance of the ISM there. They then studied the possibility that the low metal abundance may be due to the contribution of non-thermal emission, since the NE limb shows a radio-bright region (Uyaniker et al. 2004). The Cygnus Loop is one of the radio bright sources, though it is not uniform. The SE limb region of the Cygnus Loop shows no radio intensity.

We report here on the result of an observation of the SE limb of the Cygnus Loop by Suzaku, showing a similar structure in abundance to that in the NE limb.

2. Observations and Data Screening

The observation was performed on 2008 May 12. Figure 1 shows its location by a square superposed on a ROSAT image. We employed revision 2.2 of the cleaned event data and excluded the time region where the attitude was unstable. Furthermore, we excluded data taken at a low cut-off rigidity of $<6\text{ GeV} \text{c}^{-1}$. The net exposure time was 18.9 ks after screening. Since the Cygnus Loop almost extends the entire FOV, we subtracted a blank-sky spectrum obtained from the Lockman Hole, whose observation date was close to that of the Cygnus Loop (both are done in 2008 May). We found no emission above 3 keV within the statistical uncertainties.

The XIS has a contamination problem (Koyama et al. 2007), in which a contaminant is accumulated on the optical blocking filter just in front of the CCD. Although the increase of the contaminant almost terminates, the low-energy response reduces more as our observation time than that at the SWG time. A Suzaku observation of the NE limb of the Cygnus Loop was made for the first time in 2005 November, while our observation on the SE limb was carried out in 2008 May. Due to a reduction of the response at low energy, we used photons in the energy range of 0.3–3.0 keV and 0.5–3.0 keV for XIS 1 (back-illuminated CCD; BI CCD) and XIS 0, 3 (front-illuminated CCD; FI CCD), respectively. Figure 2 shows a Suzaku XIS 1 three-color image. Red, green, and blue represent the energy range of the 0.31–0.38 keV band, i.e., C $\text{VI K}_{\alpha}$, 0.38–0.46 keV band, i.e., N $\text{V I K}_{\alpha}$, 0.60–0.69 keV band, i.e.,
O VIII Kα, respectively. In the data analysis, we grouped the spectra into bins of a minimum count of 20 so that the errors were normally distributed to perform a $\chi^2$ test. Therefore, the degree of freedom (d.o.f.) depends on the statistics of the data.

3. Spatially Resolved Spectral Analysis

We divided the entire FOV into 26 square/rectangular cells shown in figure 2, such that each cell had similar statistics. We excluded the lower-right square cell, since it was almost out of the Loop. We extracted spectra from the cells and performed spectral analysis. In order to generate a response matrix file (RMF) and an ancillary response file (ARF), we employed xisrmfgen and xissimarfgen (version March 2008), respectively. The low-energy efficiency of the XIS shows degradation caused by the contaminants; however, it was taken into account when generating of the ARF file. The latest version of the response includes all of the available information after the launch (cf. Katsuda et al. 2008a).

First of all, we applied an absorbed one-$kT_e$ component of a non-equilibrium ionization model for all of the spectra (the Wabs and VNEI model in XSPEC v 12.4.0; Morrison & McCammon 1983; Hamilton et al. 1983; Borkowski et al. 1994, 2001; Liedahl et al. 1995). We noticed that many emission line features could be seen, while that emissions around 2 keV or higher were very weak. Therefore, the free parameters employed were the interstellar absorption feature, $N_H$; the electron temperature, $kT_e$; the ionization time, $\tau$; the emission measure, $EM (= \int n_e n_H dl)$, where $n_e$ and $n_H$ are the number densities of electrons and protons, respectively, and $dl$ is the plasma depth; abundances of C, N, O, Ne, Mg, Si, S, Fe, and Ni. We set the abundance of Ni equal to that of Fe, and those of Si/S equal to that of O. This model gave us fairly good fits for all of the spectra (reduced $\chi^2 < 1.3$). Maps of the best-fit parameter values are presented in figure 3.

Our data clearly show the NEI condition rather than the collisional ionization equilibrium (CIE) condition. If we set $\log \tau = 12$, where the CIE condition is achieved, we found that the reduced $\chi^2$ increased by $\sim 0.4$. Furthermore, we tried to fit data by using a CIE model (VMEKAL in XSPEC), which also shows the increase of the reduced $\chi^2$ by $\sim 0.3$ than that of the best-fit NEI model. Therefore, the spectrum in our FOV surely shows the NEI condition.

We noticed that the limb regions show higher abundance, while the temperature almost stays constant. Furthermore, they show a radial structure rather than an azimuthal structure. Therefore, we re-divided the FOV into 10 annular regions from Ann1 to Ann10, where the Ann1 is the outer-most region, as shown in figure 4. In this way, we performed a detailed spectral analysis employing the same model as described before. Figure 5 shows example spectra and their best-fit models. The reduced $\chi^2$ values are 1.2–1.7 with 250–440 d.o.f. The detailed parameters are summarized in table 1.

Figure 6 shows the variations of various parameters as a function of the angular distance from the shock front. The value of $kT_e$ is almost constant, with a slight increase towards inside. The value of $\tau$ shows an increase towards inside at the very limb region that can be seen in the forward shock front (Miyata et al. 1994). We noticed that the metal abundances in the outer annuli are much higher than those in the inner annuli. We divided the region into two groups: one being the high-abundance region (region-H: Ann1 + Ann2 + Ann3), and the other being the low-abundance region (region-L: Ann7 + Ann8 + Ann9 + Ann10). The spectra of these two regions are shown in figure 7, where we can easily see a difference in the line features. We also performed spectral analysis on them by.
using the VNEI model, and summarized the results in table 2. The abundance of O in the region-H is similar to that expected in the ISM near the Cygnus Loop (O is about 0.4 solar), while that in region-L is depleted by a factor of two, and is similar to the average abundance in the shell of the Cygnus Loop (O is about 0.2 solar). The abundances of C, N, and Ne are also high/low in the region-H/L while those of Mg and Fe are similar in the two regions. The width of the high-abundance region is about 3', which is larger than that of the PSF of the Suzaku XRT (Serlemitsos et al. 2007). The measured width is quite similar to those observed in the NE limb of the Cygnus Loop (Katsuda et al. 2008a, 2008b).

If we assume spherical symmetry of the Loop, we can expect that the plasma in the outer-most region on the apparent image will completely cover the whole Loop. Therefore, we expect that the sight line of region-L is a superposition of the plasma of the high-abundance region, and the plasma of the inside Loop. If the low abundance comes from the projection effect, we can assume that the plasma in region-L consists of two components: one being a high-abundance thermal plasma, and the other being a very low-abundance plasma, resulting in an apparent low abundance. The low-abundance plasma may come from a non-thermal origin. We then applied a combination model of VNEI and SRCUT. The SRCUT model describes synchrotron radiation from a power-law distribution of

![Image](https://example.com/image.png)

**Fig. 4.** Ten annular regions shown were employed for detailed spectral analysis.

![Image](https://example.com/image.png)

**Fig. 5.** Example spectra obtained in Ann02, Ann04, Ann06, Ann08 are shown with their best-fit models.
**Table 1.** Spectral-fit parameters for annular regions.*

| Parameter          | Ann1         | Ann2         | Ann3         | Ann4         | Ann5         | Ann6         | Ann7         | Ann8         | Ann9         | Ann10        |
|--------------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| $kT_e$ [keV]       | 0.35 ± 0.01  | 0.34 ± 0.01  | 0.38 ± 0.01  | 0.34 ± 0.01  | 0.34 ± 0.01  | 0.35 ± 0.01  | 0.35 ± 0.01  | 0.38 ± 0.01  | 0.42 ± 0.01  | 0.41 ± 0.01  |
| C (=Si = S)        | 0.60 ± 0.05  | 0.93 ± 0.06  | 0.89 ± 0.05  | 0.56 ± 0.04  | 0.47 ± 0.04  | 0.34 ± 0.03  | 0.26 ± 0.03  | 0.39 ± 0.04  | 0.40 ± 0.05  | 0.26 ± 0.03  |
| N                  | 0.85 ± 0.06  | 1.08 ± 0.06  | 0.78 ± 0.05  | 0.52 ± 0.03  | 0.32 ± 0.03  | 0.24 ± 0.02  | 0.24 ± 0.02  | 0.27 ± 0.03  | 0.40 ± 0.04  | 0.24 ± 0.03  |
| O                  | 0.44 ± 0.02  | 0.55 ± 0.02  | 0.43 ± 0.02  | 0.31 ± 0.01  | 0.21 ± 0.01  | 0.18 ± 0.01  | 0.16 ± 0.01  | 0.19 ± 0.01  | 0.22 ± 0.01  | 0.17 ± 0.01  |
| Ne                 | 0.69 ± 0.03  | 0.92 ± 0.03  | 0.70 ± 0.02  | 0.54 ± 0.02  | 0.38 ± 0.01  | 0.34 ± 0.01  | 0.30 ± 0.01  | 0.34 ± 0.01  | 0.46 ± 0.02  | 0.33 ± 0.01  |
| Mg                 | 0.5 ± 0.1    | 0.47 ± 0.09  | 0.22 ± 0.04  | 0.29 ± 0.04  | 0.18 ± 0.03  | 0.20 ± 0.03  | 0.15 ± 0.03  | 0.16 ± 0.03  | 0.21 ± 0.03  | 0.18 ± 0.03  |
| Fe (=Ni)           | 0.52 ± 0.04  | 0.39 ± 0.02  | 0.27 ± 0.01  | 0.26 ± 0.01  | 0.19 ± 0.01  | 0.18 ± 0.01  | 0.17 ± 0.01  | 0.19 ± 0.01  | 0.23 ± 0.01  | 0.19 ± 0.01  |
| log $r$ [cm$^{-3}$ s] | 10.25 ± 0.02 | 10.39 ± 0.02 | 10.52 ± 0.02 | 10.54 ± 0.02 | 10.65 ± 0.02 | 10.64 ± 0.02 | 10.7 ± 0.02  | 10.6 ± 0.02  | 10.6 ± 0.02  | 10.72 ± 0.02 |
| $EM$ [$\times 10^{58}$ cm$^{-3}$] | 3.92 ± 0.05 | 4.14 ± 0.04  | 5.41 ± 0.05  | 6.81 ± 0.06  | 10.1 ± 0.1   | 11.1 ± 0.1   | 12.4 ± 0.1   | 9.3 ± 0.1    | 7.0 ± 0.1    | 11.5 ± 0.1   |
| $\chi^2$/d.o.f.    | 392/310      | 316/254      | 429/302      | 457/313      | 390/302      | 425/298      | 433/284      | 444/257      | 343/232      | 578/444      |

* Si/S are fixed to O and other elements are fixed to those of solar values. The values of abundances are multiples of solar value. The errors are in the range $\Delta \chi^2 < 2.7$ on one parameter.

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Electrons with an exponential cut-off at the roll-off frequency, $v_{rolloff}$, (Reynolds & Keohane 1999). If we set the metal abundances to those obtained in region-H, the reduced $\chi^2$ value increased by 250 (744 d.o.f.). If we leave the abundance free, we find that the depleted abundance without the SRCUT model gives us the best-fit result. In this way, we confirmed that the simple SRCUT model does not explain the low abundance. This is consistent with the radio result that the SE limb region...
4. Discussion

4.1. Abundance Inhomogeneities in the Limb Regions of the Cygnus Loop

Past X-ray studies have shown that a heavily depleted metal abundance (O abundance is 0.1–0.2) is commonly observed in the limb of the Cygnus Loop (Miyata et al. 1994, 1998; Miyata & Tsunemi 1999; Leahy 2004; Miyata et al. 2007; Tsunemi et al. 2007, Katsuda et al. 2008a). Among them, Katsuda et al. (2008a) reported for the first time that some areas at the very edge of the NE limb show a high metal abundance (C, N, O abundance is 0.1–0.2) is commonly observed in the limb of the Cygnus Loop (Miyata et al. 1994, 1998; Miyata et al. 2007; Tsunemi & Tsunemi 1999; Leahy 2004; Miyata et al. 2007; Tsunemi et al. 2007, Katsuda et al. 2008a). Among them, Katsuda et al. (2008a) reported for the first time that some areas at the very edge of the NE limb show a high metal abundance (C, N, O abundances are ~0.7, ~0.7, and ~0.4). The high metal abundance at the very edge of the SE limb disclosed here is quite similar to that of the NE limb, and thus this is another evidence of an abundance inhomogeneity in the limb regions of the Cygnus Loop. This second discovery may almost deny a possibility that the abundance inhomogeneity in the NE limb is just an irregular exception, and suggest that such a feature may be observed in other limb regions under some specific conditions.

Here, we summarize some observational facts about the abundance inhomogeneity regions. The apparent temperature is relatively low (0.3–0.4 keV), and almost constant with a slight increase towards inside. The value of τ clearly shows the non-equilibrium condition of the plasma. The spatial distribution of τ also shows an increase from the forward shock to the inside. It is quite similar to those obtained in the NE limb regions where the abundances are high (Katsuda et al. 2008a).

The value of τ is large where the abundance is low (inside and bright region) both in the NE limb and in the SE limb. This is qualitatively understood that the regions with high $EM$ usually show high density and large values of τ. If we assume a spherical structure and uniform density of the plasma in the SE limb, we can obtain $n_e$ to be 0.4 cm$^{-3}$. With taking into account the value of τ, we can expect the elapsed time after the shock heating to be 2500 years. This rough estimate surely coincides with the cavity explosion. Levenson and Graham (2005) observed the SE region just next to our FOV, where its surface brightness is much higher than ours. They reported the CIE condition at the bright region, while they also reported the NEI condition at the very limb region showing a similar value of τ to ours.

When we see the metal abundance relative to O, the NE limb and the SE limb look quite similar to each other with an exception of Fe. In the NE limb, there is a clear difference between the abundance enhanced region and the abundance-depleted region (Katsuda et al. 2008a). They can clearly set the boundary between them based on the relative abundances of Fe/O and Mg/O. However, the boundary between them in the SE limb is not so clear, since we can hardly see a sharp variation of the relative abundances in the FOV. In this way, there are some aspects that are different in two regions. However, the abundances are quite similar to each other both in the high-abundance region and in the low-abundance region. Therefore, we expect that the origin of the plasma in the NE limb is quite similar to that of the SE limb.

The low metal abundances may be due to the combination of a thin thermal plasma with normal abundance and a non-thermal plasma. However, our data clearly supported the

| Parameter model | High region $kT_e$ [keV] | Low region $kT_e$ [keV] | High region C | Low region C | High region N | Low region N | High region O | Low region O | High region Ne | Low region Ne | High region Mg | Low region Mg | High region Fe (= Ni) | Low region Fe (= Ni) | High region $\log \tau$ [cm$^{-3}$ s] | Low region $\log \tau$ [cm$^{-3}$ s] | High region $EM$ [$10^{19}$ cm$^{-3}$] | Low region $EM$ [$10^{19}$ cm$^{-3}$] |
|-----------------|--------------------------|--------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|------------------|
| $kT_e$ [keV]    | 0.34 ± 0.01              | 0.39 ± 0.01              | 0.70 ± 0.03    | 0.38 ± 0.02    | 0.81 ± 0.03    | 0.33 ± 0.02    | 0.44 ± 0.01    | 0.19 ± 0.01    | 0.72 ± 0.01    | 0.38 ± 0.01    | 0.28 ± 0.04    | 0.24 ± 0.02    | 0.30 ± 0.01    | 0.25 ± 0.01    | 10.42 ± 0.01    | 10.77 ± 0.02    | 0.43 ± 0.01    | 1.03 ± 0.01    |

* Si/S are fixed to O and other elements are fixed to those of solar values. The values of abundances are multiples of solar value. The errors are in the range $\Delta \chi^2 < 2.7$ on one parameter.
low-abundance plasma rather than a contribution of a simple non-thermal plasma.

4.2. Comparison with the Radio Morphology

The Suzaku observation of the NE limb consists of four pointings (NE1 to NE4 from the south to the north) (Katsuda et al. 2008a). The high-abundance region is the very limb in NE3 and NE4. Their results indicate that the abundance in the NE4 limb is higher than that in the NE3 limb. According to the radio map at 1420 MHz (Uyaniker et al. 2004), the brightness temperature, $T_{\text{BR}}$, at NE1 and NE2 is one of the highest ($2\text{--}10\text{ K}$) in the Cygnus Loop, while that in NE3 is around 1 K and that in NE4 is less than 0.3 K. Therefore, we find that the region where $T_{\text{BR}}$ is low can show a high abundance in the X-ray spectrum.

Any line of sight through the remnant almost certainly intersects various emitting regions. However, the line of sight near the limb can intersect the very limited plasma condition. Therefore, we speculate that the very limb region in NE3 and NE4 contains only a thin hot plasma with a high abundance where the radio intensity is weak. We can expect that the limb region with a weak radio intensity shows high abundance that is much higher metal abundance than that in its surrounding region. The radio intensity in the Cygnus Loop is quite strong with some exceptions. One exception is the NE limb (NE3 and NE4 and its north), and the other is the SE limb. In particular, no radio intensity is reported in the SE limb (Uyaniker et al. 2004). We found that both limbs contain regions showing relatively high abundance (O is about 0.4 solar), while the inner regions show depleted abundance (O is about 0.2). The NE limb and the SE limb are similar in abundance structure, while they are quite different in radio structure.

5. Conclusion

We observed the SE limb of the Cygnus Loop with Suzaku, where the surface brightness is relatively weak and smooth. We found that the limb region (region-H) shows a relatively high abundance ($O \sim 0.4$), while that in the inner region (region-L) shows low abundance ($O \sim 0.2$). The abundance of O in region-H is similar to that of the ISM near the Cygnus Loop, while that in region-L is similar to that in the Cygnus Loop observed so far. The high metal abundance in the SE limb is quite similar to that of the NE limb, and thus this is another evidence of abundance inhomogeneity in the limb regions of the Cygnus Loop.

The radio map shows a quite different feature: the NE limb is in the radio-bright region, while the SE limb shows almost no radio. Based on the radio intensity morphology on the NE limb, we noticed that the high abundance in the very limb region (NE3 and NE4) corresponds to the weak radio intensity, while the low abundance in the very limb region (NE1 and NE2) corresponds to the high radio intensity. However, there is no radio intensity reported in the SE limb that we observed. Therefore, the non-thermal emission does not contribute to the low metal abundance both in the NE limb and in the SE limb, which are left as an open question.

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