# Suzaku Observation of the South-East Limb of the Cygnus Loop

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Abstract

We observed the south-east (SE) limb (P26, P27, and P28) of the Cygnus Loop supernova remnant (SNR) with Suzaku. The X-ray morphologies of P26 and P28 show concaved structures relative to the other shell regions of the Loop. Levenson et al. (2005) insisted that the concave seen in P26 is due to the interaction of the supernova blast wave with a large scale interstellar cloud from their Chandra observation. We perform spatially resolved spectroscopy for the Suzaku data. Applying a single temperature NEI model, we generate maps of the electron temperature, the ionization time scale, the emission measure, and metal abundances. Based on the maps, we propose that the blast wave is hitting interstellar clouds in P28 as well as P26, while the blast wave is propagating into a relatively uniform ambient medium in P26.

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

## 1. Introduction

The supernova explosion of the Cygnus Loop is generally considered to have occurred in a preexisting cavity, and the blast wave recently encountered a rigid wall of the cavity. On the other hand, in some limb regions, the blast wave seems to have overrun the cavity wall and now is proceeding into the surrounding interstellar medium (ISM).

We observed the SE limb (P26, P27, and P28; see Fig. 1) of the Cygnus Loop with Suzaku on 2008 May 13–14. The image obtained with the X-ray Imaging Spectrometer (XIS) is shown in Fig. 2, from which we can see knotty structures in P26 and P28. Levenson et al. (2005) observed the SE limb (shown in Fig. 1) by Chandra, and concluded that the SE knot is the result of the blast wave hitting a large scale interstellar cloud.

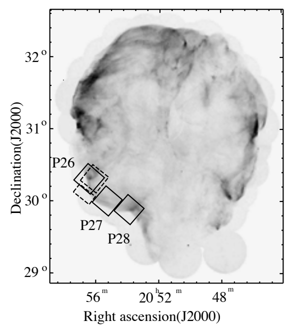


Fig. 1. ROSAT HRI image of the entire Cygnus Loop. The Suzaku and Chandra FOV are shown as solid line and dashed line, respectively.

## 2. Spatially Resolved Spectral Analysis and Results

In order to investigate the shell structure in detail, we divided the entire field of view (FOV) into a number of small cells as shown in Fig. 2, such that each cell has similar statistics (5000–10000 counts) for XIS1.

We applied an absorbed non-equilibrium ionization (NEI) model with a single temperature for all the spectra. The free parameters were foreground neutral hydrogen column density, $N_{\rm H}$; electron temperature, $kT_{\rm e}$; ionization time scale, $\tau$; emission measure, EM (EM=$\int n_{\rm e} n_{\rm H} dl$, where $n_{\rm e}$ and $n_{\rm H}$ are the number densities of electrons and protons, respectively and $dl$ is the plasma depth); and abundances of C, N, O, Ne, Mg, Si, S, Fe, and Ni. We set the abundance of Si and S equal to that of O, and Ni equal to Fe. The other elemental abundances were fixed to the solar values. This model gave us fairly good fits for all the spectra. Fig. 3 shows an example spectrum extracted from region-A indicated in Fig. 2 left.

Maps of the best-fit parameter values are presented in Fig. 4. We calculated $n_{\rm e}$ and the time elapsed since the shock passage ($t$), assuming the spherical structure and uniform density of the plasma in the SE limb.

The spatial distribution of $n_{\rm e}$ shows higher value

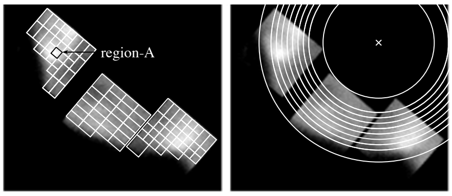


Fig. 2. Suzaku XIS0,1,3 image(0.2-10keV band). Left: A small white rectangles are the cells where we extracted spectra. Right: 9 annuli regions are shown which is employed for detailed spectral analysis.

($\sim$2cm$^{-3}$) around knots than other SE limb regions ($\sim$0.5cm$^{-3}$). The value of $t$ decreases towards the edge of the Loop. The value of $kT_{\rm e}$ in P27 increases towards the center of the Loop, while those of P26 and P28 do not show this trend.

Since the $kT_{\rm e}$-variation is seen in radial direction rather than azimuthal direction, we re-divided the FOV into 9 annular regions shown in Fig. 2 right, and then performed the detailed spectral analysis employing the same model described before. The derived values of $kT_{\rm e}$ as a function of the distance from the blast wave are shown in Fig. 5. We can see that the value of $kT_{\rm e}$ clearly increases toward the center in P27, but those in P26 and P28 seem to decrease in the same direction.

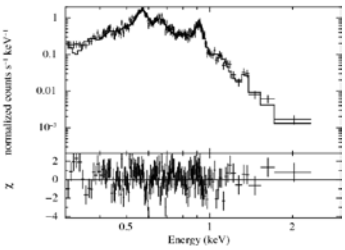


Fig. 3. X-ray spectrum of XIS1 extracted from region-A in Fig. 2. The best-fit curve is shown with the solid line.

Table 1. Spectral-fit parameters for region-A.

| | |
|---|---|
| $N_{\rm H}[10^{21}{\rm cm}^{-2}]$ . | <0.12 |
| $kT_{\rm e}$ . . . . . . . . . . | 0.337 $\pm$0.003 |
| C . . . . . . . . . . . . | 0.9 $\pm$0.1 |
| N . . . . . . . . . . . . | 0.70$\pm$0.06 |
| O(=S=Si) . . . . . | 0.31 $\pm$0.01 |
| Ne . . . . . . . . . . . | 0.57$\pm$0.02 |
| Mg . . . . . . . . . . . | 0.23$\pm$0.06 |
| Fe(=Ni) . . . . . . . | 0.21$\pm$0.02 |
| $\log(\tau/{\rm cm}^{-3}{\rm sec})$ | 10.60$\pm$0.02 |
| EM$[10^{19}{\rm cm}^{-5}]$ | 0.84 $\pm$0.01 |
| $\chi^2$/d.o.f. . . . . . . | 405/298 |

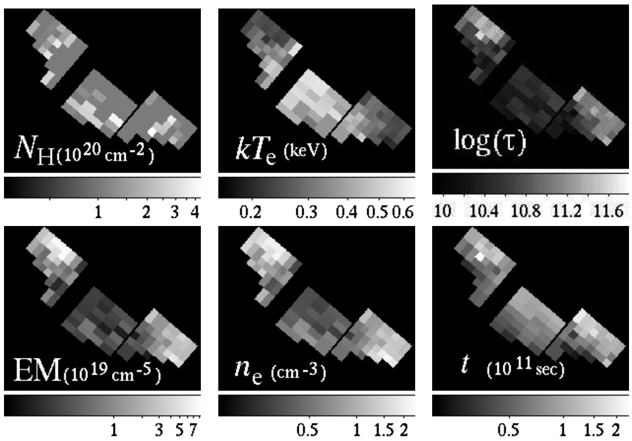


Fig. 4. Maps of best-fit parameters, $n_{\rm e}$, and $t$.

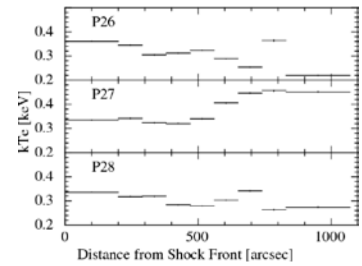


Fig. 5. $kT_{\rm e}$ is shown as a function of angular distance from the shock front.

## 3. Discussion and Conclusion

We observed the SE limb of the Cygnus Loop with Suzaku in three pointings, i.e., P26, P27, and P28. We performed spatially resolved spectral analysis for the XIS spectra. By applying a NEI model with a single temperature to the spectra, we revealed that the value of $kT_{\rm e}$ in P27 shows an increase towards inner regions of the Loop, while those in P26 and P28 seem to be higher in the outer regions where we can see knotty features in the X-ray surface brightness map. Also, we found that the values of $\tau$ and $n_{\rm e}$ in knots of P26 and P28 are higher than those of the rest of the region.

These facts suggest that in P27 the blast wave is propagating into a uniform ISM, while in P26 and P28 the blast is hitting the interstellar cloud.

## References

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