**X-Ray Investigation of the γ-Ray Excess Cygnus Cocoon by Suzaku**

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**Abstract**

A long-standing question on the origin of Galactic cosmic-rays (GCRs) is still not settled, and star-forming regions are promising sites for the production of GCRs. We conducted deep observations of nearby star-forming region Cygnus-X by Suzaku-XIS, aiming at the GeV excess revealed by Fermi-LAT.

X-ray brightness distribution, after point sources or small-scale structures are excluded, shows monotonous decrease as Galactic latitude increases, indicating that most of the extended emission is due to the cosmic X-ray background and the Galactic ridge X-ray emission. Upper limits of diffuse X-rays from the γ-ray excess are obtained and found to be not compatible with a pure electron scenario if the CR electrons producing the GeV γ-ray excess extend up to \( \sim 100 \text{ TeV} \) without cutoff.

**Key words:** cosmic-rays – gamma-rays – X-rays – star-forming regions

1. **Introduction**

One of key questions of modern astrophysics is the origin of Galactic cosmic-rays (GCRs), relativistic charged particles with energy below \( 10^{15} – 10^{16} \text{ eV} \) produced outside of the Solar System but confined inside the Milky Way. It is widely accepted that supernova remnants (SNRs) are the main source of GCRs, since they are energetic and numerous enough to maintain the power of GCRs (e.g., Ginzburg & Syrovatskii 1964). Since most of massive OB stars, progenitors of core-collapse supernovae, are born in clusters in space and time, supernova explosions occur in quasi-simultaneous. Therefore GCRs are expected to be generated and injected into the interstellar space, not by an ensemble of individual SNRs, but by overlapping SNRs (called superbubble) in star-forming regions (e.g., Butt 2009). This hypothesis of GCR origin, however, should be investigated observationally and theoretically.

Recently Large Area Telescope (LAT) onboard _Fermi_ satellite (Atwood et al. 2009) revealed an extended, hard GeV γ-ray excess called Cygnus cocoon in nearby (\( \sim 1.5 \text{ kpc} \)) star-forming region Cygnus-X (Piddington & Minnett 1952, Uyaniker et al. 2001), over standard Galactic diffuse emission and known or newly identified γ-ray sources (Ackermann et al. 2011). The residual is seen above 1 GeV with high significance (\( \geq 10 \sigma \)) and, its hard spectrum and morphology imply that the excess is interstellar origin rather than a collection of unresolved γ-ray sources. In order to explain the observed γ-ray spectrum, an amplification factor of \((1.5 - 2) \times (E/10 \text{ GeV})^{0.3} \) or \( \sim 60 \times (E/10 \text{ GeV})^{0.5} \) (where \( E \) is the energy of CRs producing the cocoon) are required for locally-measured CR protons or electrons, respectively. Such an intense, hard γ-ray spectrum points to freshly-accelerated CRs in star-forming region Cygnus-X.

2. **Observation**

Aiming to constrain properties of CRs producing the γ-ray excess, we performed a series of Suzaku observations. We conducted two source observations pointing at positions with strong GeV γ-ray excess but free of known, bright X-ray sources such as SNR γ-Cygni and X-ray binary Cyg X-3. In order to estimate the background to possible extended X-ray emission from the cocoon, particularly the Galactic ridge X-ray emission (GRXE), we also conducted two background observations. The positions of four observations are shown with a γ-ray excess count map in Figure 1. The exposures to source positions and background positions are \( \geq 40 \text{ ks} \) and \( \geq 20 \text{ ks} \), respectively, after applying standard event selection criteria and requiring the cutoff rigidity to be \( \geq 6 \text{ GV} \). The observation log is summarize in Table 1.

3. **Data Analysis and Discussion**

In order to examine the possible extended X-ray emission from the GeV γ-ray excess, we first looked up Suzaku-XIS images, identified point sources or small-scale structures, and excluded them. We then subtracted the non X-ray background (NXB) estimated by XISNXBGEN (Tawa et al. 2008). The obtained XIS spectra, inte-
Fig. 1. Positions of observations overlaid on a $\gamma$-ray excess map above 10 GeV. Source observations and background observations are shown by thick red boxes and thin green boxes, respectively. See Table 1 for details.

Table 1. Summary of observations

<table>
<thead>
<tr>
<th>Region</th>
<th>Pointing</th>
<th>Obs. date</th>
<th>exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source 1</td>
<td>79.25</td>
<td>1.5</td>
<td>2012/Nov</td>
</tr>
<tr>
<td>Source 2</td>
<td>79.0</td>
<td>1.875</td>
<td>2013/Nov</td>
</tr>
<tr>
<td>Background 1</td>
<td>78.0</td>
<td>0.75</td>
<td>2012/Nov</td>
</tr>
<tr>
<td>Background 2</td>
<td>80.5</td>
<td>2.25</td>
<td>2012/Nov</td>
</tr>
</tbody>
</table>

The NXB-subtracted X-ray spectrum is expected to be the sum of the cosmic X-ray background (CXB), the GRXE and possible X-ray emission from the cocoon. Based on Kushino et al. (2002), we included the CXB as a power-law of the photon index of 1.4 and the normalization of $6.4 \times 10^{-7}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$ in 2–10 keV (which gives the brightness of $6.4 \times 10^{-7}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$ in 2–10 keV). The GRXE is modeled by three temperature plasma (WABS*APEC) following Uchiyama et al. (2009). We did not find significant excess in the X-ray spectrum in all four pointings when we fitted data with the CXB+GRXE model described above. The possible emission from the cocoon, however, might be hidden by the model of GRXE. We therefore examined the position dependence of the CXB-subtracted brightness, and summarized the Galactic latitude dependence in Figure 2. The brightness distribution shows monotonous decrease as latitude increases, as expected for the GRXE. We therefore concluded that most of the extended emission, after the contribution of CXB is subtracted, is due to the GRXE.

Our task is then to give constraints on the extended X-ray emission from the cocoon. The lower limit of the GRXE contribution in the source positions is the brightness of Background 2, in which the Galactic latitude is the highest and hence the intensity of the GRXE should be the lowest among four positions. Therefore the robust upper limit of X-rays from the cocoon can be obtained by subtracting the brightness of Background 2, and is calculated to be $0.4 \times 10^{-7}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$ and $0.1 \times 10^{-7}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$ in 2–10 keV for Source 1 and Source 2, respectively. The expected brightness in the electron scenario to explain the GeV $\gamma$-ray excess, when the electron spectrum is extrapolated up to $\sim 100$ TeV as a simple power-law, is $\sim 0.6 \times 10^{-7}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$. Upper limits from our Suzaku-XIS observations are 1/6–2/3 of this value, and hence are not compatible with a pure electron scenario if CR electrons producing GeV $\gamma$-ray excess extend up to $\sim 100$ TeV without cutoff. Detailed modelings/discussions based on the multiwave-length spectrum including radio and TeV $\gamma$-ray data are underway.

References

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