「すざく」による白鳥座に発見されたガンマ線超過のX線探査(2)

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• Introduction (\(\gamma\)-ray excess “Cygnus cocoon”)
• Observations by Suzaku
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• Summary
Cygnus cocoon (Morphology)

- GeV $\gamma$-ray excess revealed by Fermi in star-forming region Cygnus-X
- Morphology follows the region bounded by the ionization fronts. No apparent spectral variations across the region.
- Interstellar origin rather than a superposition of unresolved sources

Ackermann+11, Science 334, 1103
Cygnus cocoon ($\gamma$-ray Spectrum)

- “Cygnus cocoon” = GeV $\gamma$-ray excess revealed by Fermi in star-forming region Cygnus-X
- Freshly-accelerated CRs are required to explain $\gamma$-ray spectrum

\[
\frac{dN}{dE}_{loc} \times (1.5 - 2) \left( \frac{E}{10 \text{ GeV}} \right)^{0.3}
\]

\[
\frac{dN}{dE}_{loc} \times 60 \left( \frac{E}{10 \text{ GeV}} \right)^{0.5}
\]

- Their origin and properties to be studied by multiwavelength obs. including X-rays

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Ackermann+11, Science 334, 1103
Observations

- We performed *Suzaku*-XIS observations to investigate properties of CRs responsible for the cocoon (particle type, spectrum, etc.)

<table>
<thead>
<tr>
<th>Region</th>
<th>Pointing(^a)</th>
<th>Net exposure (ks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source 1</td>
<td>79.25 b 1.49</td>
<td>43.3</td>
</tr>
<tr>
<td>Source 2</td>
<td>78.99 b 1.86</td>
<td>42.0</td>
</tr>
<tr>
<td>Background 1</td>
<td>78.00 b 0.74</td>
<td>19.9</td>
</tr>
<tr>
<td>Background 2</td>
<td>80.50 b 2.24</td>
<td>25.6</td>
</tr>
</tbody>
</table>

Excess $\gamma$-ray map (E>10 GeV) & X-ray observation positions

BG 2 Source 2

Source 1 BG 1
XIS Image (Source 1)

- Count map of XIS0+3, smoothed with $\sigma=0.28$ arcmin
- A few sources and/or small structures were identified and excluded to investigate the (possible) extended emission from the Cygnus cocoon

(a1) 0.4–2 keV

(a2) 2–10 keV

sources/structures

usable area
Modeling of Extended Emission (1)

- Point sources and/or small structures removed
- Non X-ray Background (NXB) subtracted (xisnxbgen)
- The remain = Cosmic X-ray background (CXB)
  + Galactic Ridge X-ray Emission (GRXE)
  + local diffuse X-rays (SWCX/Local Bubble)
  + possible emission from Cocoon
  - CXB was fixed to PL of ($\Gamma=1.4$, $N=9.4 \times 10^{-4}$ [photons/s/cm$^2$/keV]) based on Kushino+02. $N(H)=N(H_1+2H_2)=(2.5-3.1) \times 10^{22}$ [cm$^2$] was assumed based on $\gamma$-ray obs. (Ackerman+12, A&A 538, 71)
  - GRXE + local diffuse X-rays were modeled by three-temperature plasma (vapec/apec) based on previous studies
  - Then we examined residuals in spectrum to see if there are any excess (= possible emission from the cocoon)
Modeling of Extended Emission (2)

- Point sources and NXB subtracted
- The remain = CXB+GRXE+local diffuse(+possible emission from the cocoon)
  - CXB was fixed to PL of $\Gamma=1.4$.
  - GRXE + local diffuse were modeled with three-temp. plasma

CXB-subtracted intensity = $5.4 \times 10^{-8}$ [erg/s/cm$^2$/sr] @2-10 keV

No apparent excess in residual, but emission from the cocoon might be hidden by models for GRXE => examine b-dependence
Latitude Dependence of Extended Emission

- Point sources and NXB subtracted
- The remain = CXB+GRXE(+possible emission from the cocoon)
- CXB-subtracted intensity (2-10 keV) shows monotonous decrease as latitude increases (as GRXE does) even if we take the uncertainties into account

- shaded band: systematic uncertainty of assumed absorption
- error bars: uncertainties due to CXB fluctuation and NXB reproducibility

Most of (CXB-subtracted) emission comes from GRXE

($I_{BG2}=lower\ limit\ of\ GRXE\ at\ S1/S2$)
CRs to Explain Cygnus Cocoon in X- and γ-rays

- Most of CXB-subtracted emission comes from GRXE
- Conservative upper limit of X-rays from the cocoon is obtained by subtracting brightness of BG2 (=lower limit of GRXE at source positions)

Upper limit of X-rays (av. of S1 and S2)
= \(2.4 \times 10^{-8} \, [\text{erg/s/cm}^2/\text{sr}]\)
~ 1/3 of the expectation of electron scenario

γ-ray excess is due to (1) CR protons, or (2) CR electrons with cutoff at <50 TeV (in agreement with the marked decline in TeV seen \(\geq 2\) TeV)
Summary

• We observed Cygnus cocoon (γ-ray excess in Cygnus-X found by Fermi) by Suzaku-XIS
• Most of extended emission in X-rays (2-10 keV) comes from CXB+GRXE
• Conservative upper limit of X-rays from the cocoon is ~1/3 of electron scenario expectation, suggesting
  – (1) γ-ray excess is due to protons, or
  – (2) electrons with cutoff at <= 50 TeV (confirmation of the spectral cutoff inferred from TeV data)
• See the paper (arXiv:1502.01390) for more details
Reference

- Ackermann+11, Science 334, 1103
- Abdo+12, A&A 538, 71
- Kushino+02, PASJ 54, 327
- Uchiyama+09, PASJ 61, S189
- Uyaniker+01, A&A 371, 675
Backup Slides
XIS Image (Source 2)

- Count map of XIS0+3, smoothed with $\sigma=0.28$ arcmin
- A few sources and/or small structures were identified and excluded to investigate the (possible) extended emission from the Cygnus cocoon

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XIS Image (BG 1)

- Count map of XIS0+3, smoothed with $\sigma=0.28$ arcmin
- A few sources and/or small structures were identified and excluded to investigate the (possible) extended emission from the Cygnus cocoon

![Image of XIS Image (BG 1)](image-url)
XIS Image (BG 2)

- Count map of XIS0+3, smoothed with $\sigma=0.28$ arcmin
- A few sources and/or small structures were identified and excluded to investigate the (possible) extended emission from the Cygnus cocoon
Position of Observations

- Position of Suzaku observations and ROSAT ¾ keV map
Summary of Extended Emission Spectra

- Among sources identified, seven have a hard PL spectrum ($\Gamma < 2.5$) and large absorption ($N(H) > 2 \times 10^{22} \text{ cm}^{-2}$).
- (cf. 2-3 uncatalogued active galactic nuclei are expected in each XIS field-of-view)

| Source | $E_1$ (keV) | Norm$\_1$ | $E_2$ (keV) | Norm$\_2$ | $E_3$ (keV) | Norm$\_3$ | $N(H)_{\text{low}}$ ($10^{22} \text{ cm}^{-2}$) | $kT_{\text{low}}$ (keV) | $A_{\text{low}} (Z_{\odot})$ | $E_{\text{low}}$ | $N(H)_{\text{mid}}$ ($10^{22} \text{ cm}^{-2}$) | $kT_{\text{mid}}$ (keV) | $A_{\text{mid}} (Z_{\odot})$ | $E_{\text{mid}}$ | $N(H)_{\text{high}}$ ($10^{22} \text{ cm}^{-2}$) | $kT_{\text{high}}$ (keV) | $A_{\text{high}} (Z_{\odot})$ | $E_{\text{high}}$ | $I_{\text{low}} (0.5-10 \text{ keV})$ | $I_{\text{mid}} (0.5-10 \text{ keV})$ | $I_{\text{high}} (0.5-10 \text{ keV})$ | $N(\text{H})_{\text{CXB}}$ ($10^{22} \text{ cm}^{-2}$) | $I_{\text{CXB}} (0.5-2 \text{ keV})$ | $I_{\text{CXB}} (2-10 \text{ keV})$ | $I_{0.5-2}$ | $I_{2-10}$ | $\chi^2$/d.o.f. |
|--------|-------------|----------|-------------|----------|-------------|----------|----------------------------------|----------------|----------------|--------------|----------------------------------|----------------|----------------|-------------|----------------------------------|----------------|----------------|--------------|----------------|----------------|----------------|----------------|------------------|------------------|
| Source1 | 0.548 ± 0.004 | 23.8 ± 3.9 | 0.653 (fixed)$^a$ | 2.3 ± 0.8 | 6.40 (fixed) | 0.12 ± 0.10 | 0 | 0.1 (fixed) | 103 ± 18 | 0.39 ± 0.07 | 0 | 3.1 ± 1.4 | 3.1 ± 2.4 | 0.36 ± 0.22 | 106 ± 59 | 2.46 × 10$^{-8}$ | 5.66 × 10$^{-8}$ | 4.88 × 10$^{-8}$ | 2.92 (fixed) | 0.12 × 10$^{-8}$ (fixed) | 4.85 × 10$^{-8}$ (fixed) | 7.69 × 10$^{-8}$ | 10.29 × 10$^{-8}$ | 538.1/501 |
| Source2 | 0.545 ± 0.006 | 24.4 ± 3.1 | 0.648 ± 0.013 | 5.3 ± 1.1 | 6.40 (fixed) | – | 0 | 0.1 (fixed) | 144 ± 21 | 0.46 ± 0.06 | 0 | 2.6 ± 1.0 | 2.6 ± 0.4 | 0.28 ± 0.31 | 76 ± 23 | 2.86 × 10$^{-8}$ | 6.38 × 10$^{-8}$ | 3.15 × 10$^{-8}$ | 2.47 (fixed) | 0.16 × 10$^{-8}$ (fixed) | 4.97 × 10$^{-8}$ (fixed) | 9.22 × 10$^{-8}$ | 8.33 × 10$^{-8}$ | 565.7/521 |
| Background1 | 0.551 ± 0.007 | 22.1 ± 5.4 | 0.673 ± 0.031 | 2.0 ± 0.8 | – | – | 0 | 1 (fixed) | 99 ± 23 | 0.73 ± 0.11 | 0 | 2.6 ± 0.8 | 2.4 ± 0.4 | 0.19 ± 0.16 | 217 ± 78 | 2.38 × 10$^{-8}$ | 3.01 × 10$^{-8}$ | 7.20 × 10$^{-8}$ | 3.07 (fixed) | 0.11 × 10$^{-8}$ (fixed) | 4.81 × 10$^{-8}$ (fixed) | 5.72 × 10$^{-8}$ | 11.79 × 10$^{-8}$ | 320.1/252 |
| Background2 | 0.554 ± 0.010 | 14.9 ± 4.0 | – | – | – | – | 0 | 1 (fixed) | 139 ± 36 | 0.60 ± 0.02 | 0 | 2.0 ± 0.7 | 1.5 ± 0.3 | 0.4 (≤ 1.1) | 73 ± 31 | 1.55 × 10$^{-8}$ | 8.42 × 10$^{-8}$ | 2.39 × 10$^{-8}$ | 2.67 (fixed) | 0.14 × 10$^{-8}$ (fixed) | 4.92 × 10$^{-8}$ (fixed) | 10.44 × 10$^{-8}$ | 6.98 × 10$^{-8}$ | 370.5/336 |
Spectra of Point Sources

- Among sources identified, seven have a hard PL spectrum ($\Gamma<2.5$) and large absorption ($N(H)>2\times10^{22}$ cm$^{-2}$). (cf. 2-3 uncatalogued active galactic nuclei are expected in each XIS field-of-view)

Table 3: Spectra of point sources and small-scale structures

<table>
<thead>
<tr>
<th>Region/source</th>
<th>$N_H/10^{22}$ cm$^{-2}$</th>
<th>$\Gamma$</th>
<th>$kT$/keV</th>
<th>$A/Z_{\odot}$</th>
<th>$f_{0.5-2}$/erg s$^{-1}$ cm$^{-2}$</th>
<th>$f_{2-10}$/erg s$^{-1}$ cm$^{-2}$</th>
<th>$\chi^2$/d.o.f.</th>
<th>possible counterpart$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>src1</td>
<td>$0.03(\leq0.09)$</td>
<td>-</td>
<td>$0.94^{+0.08}_{-0.14}$</td>
<td>$0.07\pm0.03$</td>
<td>$1.81\times10^{-13}$</td>
<td>$0.29\times10^{-13}$</td>
<td>71.6/64</td>
<td>IRXS J202725.2+405428</td>
</tr>
<tr>
<td>src2</td>
<td>$5.1^{+2.5}_{-2.7}$</td>
<td>-</td>
<td>$2.3^{+1.0}_{-1.0}$</td>
<td>-</td>
<td>-</td>
<td>$0.03\times10^{-13}$</td>
<td>41.6/40</td>
<td>NVSS J202655+405408</td>
</tr>
<tr>
<td>src3</td>
<td>$0.79^{+0.59}_{-0.45}$</td>
<td>$\geq-2.2$</td>
<td>$0.55^{+0.48}_{-0.36}$</td>
<td>1(fixed)</td>
<td>-</td>
<td>$0.19\times10^{-13}$</td>
<td>28.1/25</td>
<td>NVSS J202723+405706</td>
</tr>
<tr>
<td>src4</td>
<td>$2.2(\leq6.7)$</td>
<td>-</td>
<td>$1.5^{+1.6}_{-1.3}$</td>
<td>-</td>
<td>-</td>
<td>$0.06\times10^{-13}$</td>
<td>16.0/25</td>
<td>TYC 3156-1302-1</td>
</tr>
<tr>
<td>src5</td>
<td>$9^{+15}_{-7}$</td>
<td>$\leq4.1$</td>
<td>$1.6^{+0.47}_{-0.43}$</td>
<td>-</td>
<td>-</td>
<td>$\leq0.01\times10^{-13}$</td>
<td>32.1/26</td>
<td>NVSS J202642+405138</td>
</tr>
<tr>
<td>src6</td>
<td>$0(\leq0.07)$</td>
<td>-</td>
<td>$1.7^{+0.47}_{-0.43}$</td>
<td>-</td>
<td>-</td>
<td>$0.48\times10^{-13}$</td>
<td>18.1/13</td>
<td>-</td>
</tr>
<tr>
<td>Source 2</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>src1</td>
<td>$2.33^{+0.86}_{-0.69}$</td>
<td>-</td>
<td>$1.58^{+0.34}_{-0.30}$</td>
<td>-</td>
<td>-</td>
<td>$0.24\times10^{-13}$</td>
<td>120.8/101</td>
<td>-</td>
</tr>
<tr>
<td>src2</td>
<td>$2.47(\text{fixed}^b)$</td>
<td>-</td>
<td>$1.23^{+0.73}_{-0.83}$</td>
<td>-</td>
<td>-</td>
<td>$0.02\times10^{-13}$</td>
<td>20.3/24</td>
<td>-</td>
</tr>
<tr>
<td>src3</td>
<td>$0.36^{+0.42}_{-0.30}$</td>
<td>-</td>
<td>$1.92^{+0.49}_{-0.41}$</td>
<td>-</td>
<td>-</td>
<td>$0.32\times10^{-13}$</td>
<td>81.7/58</td>
<td>-</td>
</tr>
<tr>
<td>Background 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>src1</td>
<td>$2.5^{+1.7}_{-1.3}$</td>
<td>-</td>
<td>$2.6^{+1.0}_{-0.9}$</td>
<td>-</td>
<td>-</td>
<td>$0.34\times10^{-13}$</td>
<td>18.0/19</td>
<td>several$^c$</td>
</tr>
<tr>
<td>src2</td>
<td>$3.1^{+8.8}_{-1.8}$</td>
<td>-</td>
<td>$0.05^{+2.05}_{-0.02}$</td>
<td>1(fixed)</td>
<td>-</td>
<td>$0.47\times10^{-13}$</td>
<td>1.1/1</td>
<td>-</td>
</tr>
<tr>
<td>Background 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>src1</td>
<td>$0(\leq18)$</td>
<td>$\leq5.4$</td>
<td>-</td>
<td>-</td>
<td>$0.15\times10^{-13}$</td>
<td>$0.79\times10^{-13}$</td>
<td>15.0/17</td>
<td>NVSS J202754+423205</td>
</tr>
<tr>
<td>src2</td>
<td>$1.5^{+3.7}_{-1.3}$</td>
<td>-</td>
<td>$0.17^{+0.89}_{-0.14}$</td>
<td>1(fixed)</td>
<td>-</td>
<td>$0.13\times10^{-13}$</td>
<td>17.5/23</td>
<td>TYC 3160-1261-1</td>
</tr>
</tbody>
</table>
Simple Argument of CR Electron Cutoff

• Conservative upper limit of X-ray emission is ~1/3 of the expectation, requiring cutoff of CR electron (in electron scenario)

Synchrotron X-ray

\[ h\nu_{\text{max, sync}} \approx 2000\left(\frac{B}{10 \mu G}\right)\left(\frac{E_e}{100 \text{ TeV}}\right)^2 \sin \theta \text{ eV} \]

For \( B=20 \mu G \), \( E_e \) of 50 TeV required to produce 1 keV X-ray

In electron scenario, cutoff in \( \leq 50 \text{ TeV} \) is required to explain (non-detection of) X-rays
• $\gamma$-ray emission = diffuse emission (ISM x Galactic CR)+point sources
• Excess is a signature of unknown high-energy objects/phenomena
• Optical from Cygnus OB2 and NGC 6910
• Infrared (dust emission) measured by IRAS