On The Origin of $\gamma$-ray Emission Toward SNR CTB 37A with \textit{FERMI LAT}

Soheila Abdollahi* | Tsunefumi Mizuno | Yasushi Fukazawa  
(Hiroshima University, Japan)  
&  
Hideaki Katagiri | Benjamin Condon

On behalf of the \textit{Fermi} LAT collaboration

7th International \textit{Fermi} Symposium  
Garmisch-Partenkirchen, Germany  
October 2017
Outline

- Mid-aged SNRs Interacting with Molecular Clouds (MCs)
- Scientific Goals
- SNR CTB 37A in Various Wavebands
- CTB 37A Analysis with Pass 8 of *Fermi* LAT
  - Source Localisation & Extension Fit
  - Spectral Analysis
- Broadband SED Modeling
- Discussion & Conclusion
Mid-aged SNRs Interacting with MCs

- Evidence of hadronic origin of the $\gamma$-ray emission in IC 443, W44, and W51C
- Expanding in dense medium as evidenced by 1720 MHz OH maser emission
- Usually as Mixed-morphology SNRs
- In most SNR/MCs, GeV $\gamma$-ray spectrum is best described by a broken power law
  - Spectral breaks at an energy of several GeV
  - Less luminous at TeV energies

CTB 37A

- A member of this category with age of $\sim 10$ kyr
- Distance of $\sim 7.9$ kpc
- Interacting with several dense MCs
- Observed non-thermal X-ray emission: signature of a PWN?

Motivations

- Origin of Galactic CRs from $\gamma$-ray observation of SNR/MCs
- Morphological study of SNR CTB 37A
- Study of Wideband spectrum
Broadband Observation of CTB 37A

VLA radio image of complex CTB 37 (Kassim et al., 1991)

Discovered in radio (Clark et al., 1975) Break-out radio morphology

Suzaku XIS image (Yamauchi et al., 2014)

Two X-ray components: a soft diffuse at the NE & a hard X-ray source in the NW

H.E.S.S. excess map (Aharonian et al., 2008)

Extended TeV emission

S. Abdollahi
Look around CTB 37A

DATA SET

- 8 years of Pass 8 data
- Energy: 200 MeV - 200 GeV
- Zmax: 105° (>1 GeV) and 90° (<1 GeV)
- ROI: 15° in radius
- Standard diffuse Galactic and isotropic models
- 3FGL catalog for background sources + CTB 37B
  - an angular distance of < 0.35° from CTB 37A
  - resolved above 10 GeV in 3FHL catalog

Previous studies:
D. Castro & P. Slane, 2010
T. J. Brandt, 2013

Highlights

- More detailed morphological and spectral studies of CTB 37A, using improved performance in Pass 8 and more accurate treatment of the nearby source CTB 37B.

Counts map (with gtlike) with a pixel size of 0.1° smoothed with σ = 0.15°
Morphological Analysis

- Best-fit Gaussian spatial model of $r_{68} = 0.18^\circ \pm 0.02^\circ$ above 0.2 GeV with LogParabola spectral shape
- A good agreement with the radio extension

TS excess map in the energy range 0.2-200 GeV in $0.9^\circ \times 0.9^\circ$

<table>
<thead>
<tr>
<th>Spatial model</th>
<th>RA</th>
<th>Dec.</th>
<th>$r_{68}$ (°)</th>
<th>TS$_{\text{ext}}$</th>
<th>Spectral Index ($\alpha$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point Source</td>
<td>258.65 ± 0.01</td>
<td>-38.54 ± 0.01</td>
<td>—</td>
<td>—</td>
<td>2.13 ± 0.01</td>
</tr>
<tr>
<td>Disk</td>
<td>258.68 ± 0.01</td>
<td>-38.56 ± 0.01</td>
<td>0.17</td>
<td>138</td>
<td>2.057 ± 0.003</td>
</tr>
<tr>
<td>Gaussian</td>
<td>258.67 ± 0.01</td>
<td>-38.55 ± 0.01</td>
<td>0.18</td>
<td>145</td>
<td>2.04 ± 0.01</td>
</tr>
</tbody>
</table>

- Reference energy ($E_b$): 1.11 GeV
- LogParabola curvature ($\beta$): 0.12
- Statistical error only is included

S. Abdollahi
Spatial model: best-fit Gaussian of $\sigma = 0.12^\circ \pm 0.01^\circ$

Systematic error is not included yet

Total energy flux in the energy range 0.2-100 GeV:

$$(90.54 \pm 2.83_{\text{stat.}}) \text{ eV cm}^{-2} \text{ s}^{-1}$$

Extrapolation of HESS data toward the LAT range slightly underpredicts the LAT measurements
Morphological Point of View:

- The TeV & X-ray offset of ~ 3.6' can be explained by breakout morphology of the remnant due to a strong density gradients
- TeV emission size of 4' ± 1' in radius
- Non-thermal X-ray emission size is consistent with the mid-aged PWNe

Spectral Point of View:

- Spectral analysis of NW hard spot:
  - Suzaku Index: 1.94 (+0.15 -0.14) typical index value of PWNe, source extraction radius: 2'
  - Chandra & XMM-Newton Index: 1.32 (+0.39 -0.35), source extraction radius: 50''
- VHE γ-ray source: spectral index of 2.30 ± 0.13_{stat.} ± 0.20_{sys.}
**Baseline Model (SNR part)**

Two independent sources: an SNR and a plausible PWN
- The radio and GeV emission with a hadronic one

**Model Characteristics:**
- Broken Power Law with a break at 10 GeV/c
- Amplified magnetic field
- Dense environment
- $W_p = 1.50 \times 10^{49}$ erg

**Similar to SNR W44**

<table>
<thead>
<tr>
<th>Hadronic Model</th>
<th>$K_p$</th>
<th>$E_{max}$</th>
<th>$B$</th>
<th>$n_H$</th>
<th>$W_p$</th>
<th>$W_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons: Broken Power Law</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha_L$</td>
<td>$\alpha_H$</td>
<td>$P_{br}$ (GeV/c)</td>
<td>$\alpha$</td>
<td>$E_c$ (GeV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>2.7</td>
<td>10</td>
<td>1.6</td>
<td>10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
 nature of the $\gamma$-ray emission: PWN Contribution

Baseline Model (PWN part)

Two independent sources: an SNR and a plausible PWN
- The X-ray and TeV emission with energetic leptons

Suzaku by looking at a relatively large region can sample both young and old population of electrons

- 1$^{\text{st}}$ hump in X-ray via synchrotron radiation of younger and high energetic electrons
- 2$^{\text{nd}}$ hump in TeV via ICS of CMB photons by older and less energetic electrons

Leptonic Model

<table>
<thead>
<tr>
<th>$K_{ep}$</th>
<th>$B$</th>
<th>$W_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrons: PL with Super Exp. Cut-off</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$E_e$</td>
<td>$\beta$</td>
</tr>
<tr>
<td>2.30</td>
<td>9.5E+04</td>
<td>0.65</td>
</tr>
</tbody>
</table>

PRELIMINARY
Broadband SED Modeling of CTB 37A: Summation of SNR & PWN models
Summary & Conclusion

• CTB 37A extension:
  - Best-fit Gaussian model of $r_{68} = 0.18° \pm 0.02°$ is favored over a point-like source with $T_{S_{ext}} = 145$.

• Nature of $\gamma$-ray emission:
  - GeV emission can not connect to the TeV emission, smoothly.
    → Suggests two different origins for GeV and TeV emission

• Implication of the multi-wavelength spectrum: an SNR + a PWN
  - Non-thermal X-ray and TeV emission can be explain by a plausible PWN
  - Radio and GeV emission from the SNR

• SNR model Characteristics:
  - Broken power law spectrum of proton with a break at 10 GeV/c and index of 2.1 before break and 2.7 after break.
  - Amplified magnetic field of 350 $\mu$G
  - $W_p = 1.50 \times 10^{49}$ erg
BACK-UP
## Spectral Energy Distribution

<table>
<thead>
<tr>
<th>$E_{\text{min}}$ (GeV)</th>
<th>$E_{\text{max}}$ (GeV)</th>
<th>SED (MeV cm$^{-2}$ s$^{-1}$)</th>
<th>TS</th>
<th>$N_{\text{pred}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.200</td>
<td>0.430</td>
<td>1.03E-05</td>
<td>136.76</td>
<td>5843</td>
</tr>
<tr>
<td>0.430</td>
<td>0.930</td>
<td>1.91E-05</td>
<td>670.65</td>
<td>6630</td>
</tr>
<tr>
<td>0.930</td>
<td>2.0</td>
<td>2.08E-05</td>
<td>1158.68</td>
<td>4325</td>
</tr>
<tr>
<td>2.0</td>
<td>4.31</td>
<td>1.62E-05</td>
<td>836.10</td>
<td>1666</td>
</tr>
<tr>
<td>4.31</td>
<td>9.28</td>
<td>1.16E-05</td>
<td>404.95</td>
<td>542</td>
</tr>
<tr>
<td>9.28</td>
<td>20.0</td>
<td>5.91E-06</td>
<td>101.24</td>
<td>129</td>
</tr>
<tr>
<td>20.0</td>
<td>43.090</td>
<td>4.63E-06</td>
<td>40.34</td>
<td>47</td>
</tr>
<tr>
<td>43.090</td>
<td>92.830</td>
<td>2.04E-06</td>
<td>5.22</td>
<td>9</td>
</tr>
<tr>
<td>92.830</td>
<td>200.0</td>
<td>0&lt; 4.62E-06</td>
<td>0.65</td>
<td>2</td>
</tr>
</tbody>
</table>

*Upper limits for TS < 4*
## Model Parameters of Several SNR/MC

<table>
<thead>
<tr>
<th>Model Parameter</th>
<th>W51C(^1)</th>
<th>W44(^2)</th>
<th>W28(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Hadronic)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (10(^4) yr)</td>
<td>3.0</td>
<td>2.0</td>
<td>4.0</td>
</tr>
<tr>
<td>d (kpc)</td>
<td>6</td>
<td>3.1</td>
<td>2.0</td>
</tr>
<tr>
<td>B ((\mu)G)</td>
<td>40</td>
<td>210</td>
<td>160</td>
</tr>
<tr>
<td>n_H (cm(^{-3}))</td>
<td>10</td>
<td>300</td>
<td>100</td>
</tr>
<tr>
<td>K_{ep}</td>
<td>0.02</td>
<td>0.01(^\dagger)</td>
<td>0.01</td>
</tr>
<tr>
<td>(\alpha_L)</td>
<td>1.5</td>
<td>2.2\pm0.1</td>
<td>1.7</td>
</tr>
<tr>
<td>(\alpha_H)</td>
<td>- - -</td>
<td>3.2\pm0.1</td>
<td>2.7</td>
</tr>
<tr>
<td>(\Delta\alpha)</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio Spectral Index</td>
<td>-0.26</td>
<td>-0.37</td>
<td>-0.35\pm0.18</td>
</tr>
<tr>
<td>E_b (GeV)</td>
<td>15</td>
<td>20\pm1</td>
<td>2</td>
</tr>
<tr>
<td>(W_p) (10(^{49}) erg)</td>
<td>52</td>
<td>5</td>
<td>1.3</td>
</tr>
<tr>
<td>(W_e) (10(^{49}) erg)</td>
<td>1.3</td>
<td>5.6\times10^{-2}</td>
<td>1.9\times10^{-2}</td>
</tr>
</tbody>
</table>

\(^1\)W51C: A. A. Abdo et al., 2009, ApJL, 706, L1


\(^\dagger\)at 10 GeV

Note: For the leptonic contribution: a simple PL with cut-off for electrons with \(\alpha = 1.74\) and \(E_c = 12\pm1\) GeV

\(^3\)W28: A. A. Abdo et al., 2010, ApJL, 718, 348