Fermi LAT Observations of GeV Gamma Rays from Supernova Remnants

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on behalf of Fermi LAT collaboration
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Observations of GeV gamma rays are crucial for study of cosmic-ray acceleration in SNRs.

- Parent particles, momentum spectrum, diffusion...

Aharonian et al. (2006)

**Observations of GeV gamma rays from SNRs**

**SNR RX J1713.7-3946**

**Leptonic model**

**Hadronic model**
Before the Fermi-LAT ~ SNR W28 case

- The uncertainty of position determination accuracy ~ 1deg. due to degree-scale PSF and low statistics
- Point-source or extended?
- Spectral studies at > a few GeV are limited due to the small effective areas.

Green contours: 4, 5, 6 sigmas of the HESS TeV emissions
Fermi Gamma-ray Space Telescope

- International collaboration between US, Europe, and Japan
- Launched on June 11 2008 (its science data is public now)
- Consists of LAT and GBM

Large Area Telescope (LAT)

Tracker (16 towers):
- Pair conversion telescope
  → Tungsten conversion foils
- Measures $e^-/e^+$ track with Si-strip detectors

- Better PSF ($\sim 0.6^\circ @ 1$GeV)
- Large Eff. Area & 2.4 sr FoV
- $\sim 20$ MeV < $E$ < $\sim 300$ GeV

Calorimeter:
- 1536 CsI crystals
- Measures photon energy

Anti-coincidence detector:
- Segmented
- Vetos CR background

Source ID & extension
Emission mechanism
GeV-emitting SNRs

- 10 SNRs so far (W28, W49B, RX J1713-3946, G8.7-0.1, ...)
- Two categories
  - Young (<\~2000yr) SNRs (Cas A, RX J1713-3946)
  - Relatively old SNRs with molecular clouds (W28, W44, W49B, W51C, IC443, etc.)
Young SNR $\sim$ Cas A

- Historical supernova: age=330yr
- The brightest radio source in our Galaxy
  - $\rightarrow$ efficient particle acceleration
- TeV gamma rays detected by HEGRA, MAGIC, VERITAS

- Cannot be distinguished on positional grounds
- No gamma-ray pulsation, no time variability
- No pulsar-like cutoff on the spectrum

GeV gamma rays
$\sim$ from the SNR shells.

Abdo et al. (2009)
Corresponding Authors (CAs): Funk, Uchiyama
Spectrum of Cas A

- **Leptonic scenario (Brems + IC):**
  - \( B = 0.12 \, \text{mG}, \, W_\text{e} = 1 \times 10^{49} \, \text{erg} \)

- **Hadronic scenario (\( \pi^0 \) decay):**
  - \( B > 0.12 \, \text{mG}, \, W_\text{p} = 3 \times 10^{49} \, \text{erg} \)
  - Good fit with proton spectral index \( \sim 2.3 \)
  - (red) or \( \sim 2.1 \) (blue) with cut-off at 10 GeV

- The hadronic scenario can better fit the data (but not conclusive due to the systematics)
- \( W_\text{CR}(e+p) = 1-4 \times 10^{49} \, \text{erg} \) regardless of the parent particles.
- \( B > 0.12 \, \text{mG} \) \( \rightarrow \) B amplification at the shock
W44

- Mixed morphology SNR
- Age $\sim 2 \times 10^4 \text{yr}$
- Distance $\sim 3 \text{kpc}$
- Interactions with molecular clouds

Lines from H$_2$ gas (Spitzer)
Radio synchrotron (VLA)
★ OH masar spots

Castelletti+07

$\sim 0.5^o$
Results of maximum likelihood analysis also prefer ring-like morphology rather than centrally filled morphology (> 8σ).
LAT spectrum & modeling

- $\pi^0$-decay model can explain the data well
  - Leptonic scenarios have difficulties
    - Brems: difficult to reconcile with the radio data
    - IC: large amount of electrons ($\sim 10^{51}$ ergs)
- Protons need to have a spectral break at $\sim 10$ GeV/$c$
  - Possible explanation:
    Fast escape of high energy particles with damping of magnetic turbulence due to the dense environment (e.g. Ptuskin & Zirakashvili 2003)
Comparison of energy spectra

Different evolutionary stages allows us to probe how particles are accelerated and later released into the Galaxy.
W28 (G6.4-1.0)

- Mixed-morphology SNR
- Old age ~35000-150000yr
- Distance 1.8-3.3kpc
- TeV detected by HESS
- South TeV sources are spatially coincident with star forming regions.

Aharonian et al. (2008)
Association with molecular clouds

NANTEN 12CO(J=0-1) 0-10km (0 – 2.5 kpc)

NANTEN 12CO(J=0-1) 10-20km (2.5 – 4 kpc)

Most outstanding in the gamma-ray (HESS) – CO correlation among SNRs.

Aharonian et al. (2008)
LAT view

Abdo+10 (CAs: Katagiri, Tajima, Tanaka, Uchiyama)

- The GeV emission is extended, overlapping with molecular clouds
- Spectral steepening with a break ~1GeV.
- $\pi^0$-decay in dense molecular gas provides a reasonable explanation for the broadband gamma-ray spectrum (similar to W44, etc.).
- The compact HII region W28A can be a possible energy source with extremely high density ($\sim10^7$/cc).

- Mosaic: FERMI (1pixel=0.025deg. Smoothing Gaussian kernel=0.2deg.)
- Contours: NANTEN (CO J=1-0) v=0-20km/s (25, 50,75%)
- Diamonds : HII regions
Comparison with TeV

- Upper limits in the GeV band on HESS J1800-240A, C

- Mosaic: FERMI (1 pixel = 0.025 deg. Smoothing Gaussian kernel = 0.2 deg.)
- Contours: HESS excess map (20, 40, 60, 80%) with smoothing (Gaussian kernel = 0.1 deg.)
- A, B, C = HESS J1800-240A, B, C
- Diamonds: HII regions
Runaway CRs?

- Nearby clouds (surrounding material)
  - GeV > TeV

- Distant clouds
  - GeV < TeV

GeV-TeV spectrum allow us to study CR diffusion.

![Gamma-ray spectra from the SNR](image)

Fig. 1.—Gamma-ray spectra from the SNR (top) and from a cloud of $10^4 M_\odot$ located 100 pc away from the SNR (bottom). The distance is 1 kpc. Curves refer to different times after the explosion: 400 yr (curve 1), 2000 yr (curve 2), 8000 yr (curve 3), and $3.2 \times 10^4$ yr (curve 4) yr.
SNR with TeV & MCs
\(~G8.7-0.1\)

Extended GeV emission
Spatially associated with some molecular clouds
With relatively bright TeV emission (~25% Crab)

Abdo et al. (CAs: Hanabata, Katagiri), to be submitted
Theoretical activities

- Runaway CRs (e.g., Fujita+10, Ohira+10) See Ohira-san’s talk
  - CRs escaping from SNR and colliding with nearby MCs
- “Crushed cloud” scenario (Uchiyama+10)
  - Gamma rays coming from “cloud shock” (CRs and MC simultaneously compressed)
  - Spectral break: Ion-neutral collision $\rightarrow$ Damping of Alfvén wave
  - Radio-GeV correlation naturally explained
- Etc.
Summary of the LAT SNRs

Compiled by Uchiyama

<table>
<thead>
<tr>
<th>Object</th>
<th>Diameter</th>
<th>Age</th>
<th>Cloud Interaction</th>
<th>$L_\gamma$ 1-100 GeV</th>
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</thead>
<tbody>
<tr>
<td>Cas A</td>
<td>5 pc</td>
<td>330 yr</td>
<td>No</td>
<td>4x10^{34} erg/s</td>
</tr>
<tr>
<td>W49B</td>
<td>10 pc</td>
<td>~3000 yr</td>
<td>Yes</td>
<td>9x10^{35} erg/s</td>
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<tr>
<td>3C 391</td>
<td>15 pc</td>
<td>~6000 yr</td>
<td>Yes</td>
<td>6x10^{34} erg/s</td>
</tr>
<tr>
<td>G349.7+0.2</td>
<td>17 pc</td>
<td>~6000 yr</td>
<td>Yes</td>
<td>9x10^{34} erg/s</td>
</tr>
<tr>
<td>IC 443</td>
<td>20 pc</td>
<td>~10000 yr</td>
<td>Yes</td>
<td>8x10^{34} erg/s</td>
</tr>
<tr>
<td>W44</td>
<td>25 pc</td>
<td>~10000 yr</td>
<td>Yes</td>
<td>3x10^{35} erg/s</td>
</tr>
<tr>
<td>W28</td>
<td>28 pc</td>
<td>~10000 yr</td>
<td>Yes</td>
<td>9x10^{34} erg/s</td>
</tr>
<tr>
<td>CTB 37A</td>
<td>50 pc</td>
<td>~20000 yr</td>
<td>Yes</td>
<td>9x10^{34} erg/s</td>
</tr>
<tr>
<td>G8.7-0.1</td>
<td>63 pc</td>
<td>~30000 yr</td>
<td>Yes</td>
<td>8x10^{34} erg/s</td>
</tr>
<tr>
<td>W51C</td>
<td>76 pc</td>
<td>~30000 yr</td>
<td>Yes</td>
<td>8x10^{35} erg/s</td>
</tr>
</tbody>
</table>


- Some of their emissions are well-explained by $\pi^0$ decay by making detailed discussion (spectral modeling, association, etc.).
- Observationally biased to SNRs with clouds so far.
- Deeper observation would provide less-biased samples.
Fainter SNRs with deeper observations ~ Cygnus Loop

- Middle-aged shell-type SNR
- Large offset from the Galactic plane -> shock regions well-studied by IR/optical/UV
- Large size ~ 3°
  - Can be easily compared with other waveband data to study particle acceleration.
- Nearby SNR ~540pc; well-determined by optical filaments (Blair+05)
  - Could leave a unique feature in the CR electron spectrum of 1-2 TeV in the vicinity of the Earth (Koboyashi’03).
The largest gamma-ray-emitting SNR
- Detailed morphological study
- Without clear correlation with dense molecular clouds
- A valuable sample for particle acceleration

Abdo et al. (CAs: Katagiri, Tibaldo), to be submitted

LAT view

0.5-10GeV with ROSAT X-ray contours
Fermi to CTA

- Better source identifications by extension with better PSF (2’ at 1TeV)
  - Extension is a useful to constrain a pulsar/PWN hypothesis.
  - Associations with molecular clouds, shells, etc.

- Sensitivities of current TeV experiments are not sufficient to search for all SNRs in our Galaxy.
  - Most of SNRs would have a steep spectrum, except for young ones.

See Bamba-san’s talk (including some quantitative estimations)
Summary

- The Fermi-LAT detected GeV gamma rays from ~10 SNRs with 2 yr data.
- Two types:
  - (1) Young SNRs, (2) relatively old SNRs with MCs.
- Basically gamma rays are naturally explained by $\pi^0$ decay with surrounding material or molecular clouds.
- CR diffusion & environment in acceleration region can be also investigated.
- Deeper observations would provide less-biased samples for study of CRs.
- The CTA will extend detailed studies of CR acceleration to much more SNRs in our Galaxy with better angular resolution & sensitivity.