FERMI-LAT STUDY OF SUPERNOVA REMNANTS

Y. Uchiyama (SLAC) on behalf of the Fermi LAT collaboration
CR Acceleration in Young SNRs

- **Diffusive Shock Acceleration** (1st order Fermi Acceleration) at expanding supernova shells is the most-favored explanation for the origin of galactic cosmic rays (CRs).

- Significant progress in recent years by keV and TeV observations of young SNRs.

**SNR RXJ1713.7-3946**

**Non-linear Acceleration**

Berezhko&Völk 2006

**Synchrotron X-ray variability**: \( B \approx 0.1 - 1 \text{ mG} \)

Uchiyama+2007

**Filament width**: \( B \approx 0.1 \text{ mG} \)

Gamma-ray emission mechanism is under active debate.
Collisionless Shock in SNRs

**Shock Heating**

- **Thermal ions**
  - Maxwellian distribution: $kT_i$
  - Coulomb + ?

- **Thermal electrons**
  - Maxwellian distribution: $kT_e$

\[ kT_i > kT_e \]

in young SNRs

**Shock Acceleration**

- **Cosmic Rays**
  - Power law distribution:
    - total energy
    - max/min energy
    - number index

- **Fermi Acceleration**
- **Bell hypothesis**
- **Magnetic Fields**
  - total energy
  - max/min scale
  - index (e.g. Kolmogolov)

Calculations from “first principle”: not available
We need Experiments (Observations)!!
Indirect Evidence of CR Dominance

SNR RCW 86 (The remnant of SN AD 185)

Helder+2009

VLT (Hα filaments)

Line width gives a post-shock temperature of 2.3±0.3 keV

Chandra (Synchrotron X-ray)

Proper motion predicts a post-shock temperature of 42 - 70 keV

CR pressure seems comparable to thermal pressure
Large amount of shock energy goes to CRs

Fermi-LAT observations will be able to test this.
Fermi Study on SNRs

Key issues to be addressed by Fermi LAT:

- Searching for pion-decay signatures,
- Measuring total CR energy content per SNR,
- Measuring CR spectrum,
- Learning how CRs are released into ISM.

(Typical) Gamma-ray Spectrum

- $D = 3$ kpc
- $n = 100$ cm$^{-3}$
- $W_p = 10^{49}$ erg
- $W_e = 10^{47}$ erg
- $E_{p,\text{max}} = E_{e,\text{max}} = 0.5$ TeV
- Particle index = 2.0 (solid)
- Particle index = 2.3 (dashed)

Interaction with molecular cloud enhances Pion-decay/Bremsstrahlung.
### IC 443: (A. Rodriguez on behalf of Fermi LAT at 31st ICRC)
- Middle Age, Mixed Morphology SNR, Distance 1.5 kpc
- Interactions with Molecular Cloud
- EGRET, AGILE, MAGIC, VERITAS
- **Fermi-LAT** (0FGL J0617.4+2234: 3 months data yield \(51 \sigma\))

### W44: (T. Tanaka on behalf of Fermi LAT at 31st ICRC)
- Middle Age (20000 yr), Mixed Morphology SNR, Distance 3 kpc
- Interactions with Molecular Cloud
- EGRET
- **Fermi-LAT** (0FGL J1855.9+0126: 3 months data yield \(39 \sigma\))

### W51C: (Y. Uchiyama on behalf of Fermi LAT at 31st ICRC)
- Middle Age (20000 yr), Distance 6 kpc
- Interactions with Molecular Cloud
- HESS (No spectrum)
- **Fermi-LAT** (0FGL J1923.0+1411: 3 months data yield \(23 \sigma\))
SNR W51C

- ROSAT X-ray (color), VLA (contours)
- D ~ 6 kpc, Age ~ 20000 yrs
- Molecular cloud interactions
- SNR diameter ~ 30 arcmin
  ... may be extended for LAT at high energies
- very large: 90 pc x 70 pc

- Very recent HESS detection

Star-forming region W51B overlaps with SNR W51C (W51B is likely interacting with SNR W51C)

Supernova exploded in the vicinity of star-forming regions (?)
Fermi View on W51C Region

Fermi LAT counts map: very bright (>40 $\sigma$) gamma-ray source

Preliminary
Close-up View on W51C Region

**Color:** Fermi LAT counts map (2-8 GeV)
Black contours: ROSAT X-ray map (0.1-2.4 keV)
Green contours: VLA 1.4 GHz

**X-ray:**
- Thermal emission by shock-heated plasma (kT=0.2 keV)
- Central region due to cloud evaporation?

**Radio:**
- Peaks are HII regions
- Synchrotron radiation of SNR W51C is well matched with thermal X-ray emission

**GeV Gamma-ray:**
- Origin?
- Very large luminosity (~4×10^{35} erg/s) using 6 kpc

**X:** CXOJ192318.5+140305 (a neutron star?)
The Fermi Source is “Extended”

- Mean surface brightness (2-8 GeV) as a function of distance from the SNR center vs Fermi-LAT PSF (using the energy spectrum obtained with maximum likelihood technique).

(Note) PSF of Fermi LAT depends heavily on energy. The PSF shape is obtained by taking account of energy distribution.
SNR W44

- Middle-aged (~ 2.0 × 10^4 yr)
- Mixed-morphology SNR (radio: shell, thermal X-ray: centerly filled)
- Distance: ~ 3kpc
- Spatial extent: ~ 35 arcmin × 26 arcmin

Bright radio source (S_{1GHz} ~ 230 Jy)
Filamentary shell structures

Interactions with a giant molecular cloud
CO (Seta et al. 2004),
OH maser (1720 MHz: Hoffman et al. 2005),
IR(shocked H2; Reach et al. 2006)

Spitzer 4.5 microns
Reach+2006
SNR W44

Interactions with a giant molecular cloud

Seta+2004
Pulsar & PWN in W44

- Associated pulsar: PSR B1853+01 (Wolszczan+1991)
- Characteristic age: $\sim 2.0 \times 10^4$ yr

Black cross: location of PSR B1853+01

Castelletti+2007
W44 Region: Fermi-LAT Image

Fermi-LAT Smoothed Count Map (Front Events; 2–10 GeV)
The source corresponds to 0FGL J1855.9+0126 (BSL: Abdo et al. ApJS 2009)
Black cross: PSR B1853+01 (No evidence of pulsed gamma-rays)
Spatial Extention (1)

Smoothed Count Map (> 1GeV)

Profile along SE-NW
Contributions from the diffuse backgrounds and nearby sources are subtracted

Red: Observed Counts
Black: Expected Profile for a Point Source

Spatially Extended

Black Cross: Pulsar (PSR B1853+01) location
Spatial Extention (2)

Smoothed Count Map (> 1GeV)

Profile along NE-SW

Black Cross: Pulsar (PSR B1853+01) location

Red: Observed Counts

Black: Expected Profile for a Point Source

Preliminary
Fermi-LAT has started to reveal spatial structures of some bright gamma-ray sources. We can obtain even better images by applying a kind of maximum likelihood technique.
EGRET Study on SNRs

**W28**

0FGL J1801.6-2327

**LAT PSR J2021+4026**

**ICRC talk by Tanaka (Fermi LAT)**

**W44**

0FGL J1855.9+0126

**LAT Bright Source List**

EGRET 95% error circles

**γ -Cygni**

0FGL J0617.4+2234

**IC443**

ICRC talk by Rodriguez (Fermi LAT)

Despite its brightness at GeV energies, the Fermi source in the W51C region does not have EGRET counterpart(s).
Summary

- Results of Fermi-LAT observations of the W44/W51C regions are presented
- Gamma-rays are spatially “extended”
- Positionally coincident with SNRs
- Gamma-ray luminosity is found to be very large (e.g. \( \sim 4 \times 10^{35} \) erg/s for W51C):
  - One of the most luminous extended gamma-ray sources in the Galaxy
- Spectral analysis will be presented in a refereed journal