Observation of Supernova Remnant IC 443 using the Fermi Large Area Telescope

Herman Lee[1], Tsuneyoshi Kamae[1], Diego F. Torres[2], Ana Y. Rodriguez[2], Francesco Giordano[3,4]
on behalf of the Fermi Large Area Telescope Collaboration

[1] Kavli Institute for Particle Astrophysics and Cosmology, Department of Physics and SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94305, USA
[2] Institut de Ciencies de I'Espai, Campus UAB, 08193 Barcelona, Spain
[3] Istituto Nazionale de Fisica Nucleare, Sezione di Bari, 70126 Bari, Italy
[4] Dipartimento di fisica 'M. Merlin' dell'Universita' e del politecnico di Bari, I-70126 Bari Italy

Summary – We report a high-significance detection of the Supernova Remnant (SNR) IC 443 by the Fermi Large Area Telescope with unprecedented angular resolution in the 200 MeV to 50 GeV energy range. With the high statistics of gamma-ray photons available, we accurately characterize the high energy emission produced by the cosmic-ray particles accelerated by IC 443 both spatially and spectrally to provide constraints on the possible underlying emission mechanisms as well as the astrophysics involved with SNRs interacting with molecular clouds in general. **(Submitted to *The Astrophysical Journal*)**

Abstract

We report observation of the supernova remnant IC 443 (G189.1+3. 0) with the *Fermi Gamma-ray Space Telescope (FGST)* Large Area Telescope (LAT) in the energy band between 200 MeV and 50 GeV. IC 443 is a shell-type supernova remnant located off the outer Galactic plane where high-energy emission has been detected in the X-ray, GeV and TeV gamma-ray bands. Past observations suggest IC 443 has been interacting with surrounding interstellar matter. Proximity between dense shocked molecular clouds and GeV – TeV gamma-ray emission regions detected by *EGRET*, *MAGIC* and *VERITAS* suggests the interpretation that cosmic-ray (CR) particles are accelerated at IC 443. With the high gamma-ray statistics and broad energy coverage provided by the LAT, we accurately characterize the gamma-ray emission produced by the CRs accelerated by IC 443. The emission region is extended in the energy band with $\theta_{68} = 0.27^{\circ} \pm 0.01^{\circ}$ (stat) $\pm 0.03^{\circ}$ (sys) for an assumed 2-dimensional Gaussian profile and overlaps almost completely with the extended source region of *VERITAS*. Its centroid is displaced significantly from the known pulsar wind nebula (PWN) which suggests that the PWN is not a major contributor in the present energy band. The observed spectrum changes its power-law shape continuously and continues smoothly to the *MAGIC* and *VERITAS* data points. The combined gamma-ray spectrum (200 MeV < E < 2 TeV) is reproduced well by decays of neutral pions produced by a broken power-law proton spectrum with a break at around 70 GeV.

Introduction – IC 443 (G189.1+3.0) is a well-studied middle-aged supernova remnant (SNR) located at the outer Galactic plane in the anti-center direction. Like several other Galactic SNRs (e.g. W28, W44 and Kes 27), it possesses an interesting mixed-morphology (Rho & Petre 1998) which shows up center-filled in soft thermal X-ray (e.g. Kawasaki et al. 2001) but has a contrasting shell-like structure in the radio and optical bands (e.g. Leahy 2004). Strong molecular lines and OH masers (e.g. Dame et al. 2001) have been observed along the same direction, which implies the presence of a group of foreground molecular clouds. This makes IC 443 one of the best candidates for studying non-relativistic collision-less shocks, and the accelerated cosmic rays (CR) therein, interacting with dense molecular clouds. Co-spatial high energy gamma-ray photons have been detected by *EGRET* (Hartman et al. 1999) as well as ground Cherenkov telescopes – *MAGIC* (Albert et al. 2007) and more recently *VERITAS* (Acciari et al. 2009), whose origin is crucial to unveiling the unresolved role of SNRs in the production of Galactic cosmic rays. This observation of IC 443 using the Fermi Large Area Telescope (LAT) fills up the important energy range between 200MeV and 50GeV with an unprecedented angular and energy resolution, providing invaluable information for our understanding on this kind of SNR/cloud systems and the origin of Galactic CRs in a broader sense.

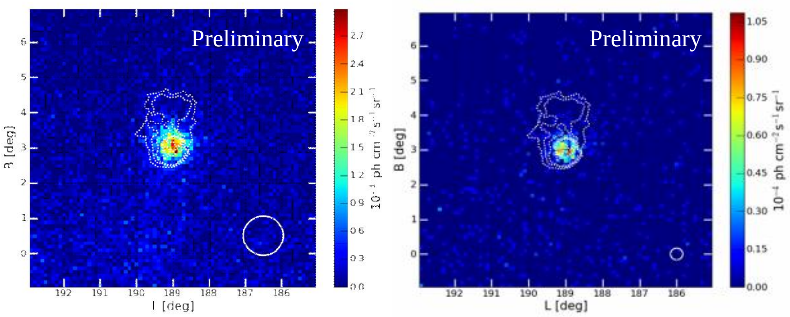

Fig. 1 – Intensity maps of the IC 443 region observed by LAT in the 1 – 5 GeV (left panel) and the 5 – 50 GeV (right panel) energy bands. Color scales have units of 10^{-4} ph/cm²/s/sr. The circles in the bottom-right corner show the spectrum-weighted PSF (θ_{68}) of LAT for the respective energy band. The 2.7 GHz radio continuum observation by Furst et al. (1990) is also shown by the overlaid white contours.

Observation – Gamma ray selection criteria are summarized in Table 1. The data set contains 11-month worth of observation starting from August 2008 till June 2009. The chosen ROI is centered at the best-fit centroid of the source (see below) at (l, b) = (189.05°, 3.03°), which for localization and extension analysis is energy-dependent, with a maximum radius of 15° at 200MeV and a minmum of 3.5° at 50GeV, to optimize signal-to-noise ratio; but is fixed independent of energy within a 8° x 8° square field for spectral analysis using binned *GTLIKE*. The observed gamma-ray intensity distributions of the IC 443 region are shown in Fig. 1 in two energy bands within the 8° x 8° square field. Integrated over energy and exposure, gamma-ray emission from IC 443 is detected at ~ 86 σ statistical level.

Time Period (MET)	239557417 – 268416079
Energy Range	200 MeV – 50 GeV
Region-of-Interest	≦ 15° in radius
Photon Class	*Pass 6 Diffuse*
Additional Cut	Zenith angle ≦ 105°

Table 1 – Event selection for the analysis

Preliminary

Energy	l (°)	b (°)	θ_{68}^{error} (°)	$\theta_{68}^{extension}$ (°)	$\theta_{95}^{extension}$ (°)	$TS_{extension}$
1 – 5 GeV	189.05	3.05	0.02	0.27 ± 0.03	0.44 ± 0.04	+106 / +121
5 – 50 GeV	189.06	3.00	0.03	0.26 ± 0.04	0.42 ± 0.07	+81 / +212
1 – 50 GeV	189.05	3.03	0.02	0.27 ± 0.03	0.45 ± 0.05	+212 / +362

Table 2 – Centroid and Extension of IC 443 fitted using a two-dimensional symmetric Gaussian with maximum likelihood method. $TS_{extension}$ is the likelihood ratio ($-2\Delta\log(\text{likelihood})$) between the best-fit extended model (Gaussian) and a point source hypothesis. The two values shown are the lower and higher obtained with the ideal-case PSF (*P6_V3_DIFFUSE*) and the worst-case PSF (In-Flight)

Preliminary

Model	γ_1	γ_2	E_{Break} (GeV)	F_{200} (10^{-7} ph/cm²/s)	χ^2/ndof
Broken PL	1.93 ± 0.03	2.56 ± 0.11	3.25 ± 0.60	2.85 ± 0.07	8.9 / 9
PL	2.08 ± 0.02	-	-	3.00 ± 0.07	90 / 11

Table 3 – Spectral fitting results for the IC 443 component

Spatial Analysis – With the angular resolution of LAT, IC 443 shows up as an extended source. We use a tool dedicated for source extension determination using maximum likelihood – '*Sourcelike*' for our analysis (please see presentation by Joshua Lande for details of the tool). We divide the 1 GeV to 50 GeV energy band into 10 log-uniform bins. Sub-GeV photons are not as useful for spatial study due to their relatively large PSF. Diffuse emission and isotropic backgrounds, for which we adopt the latest 'ring model' result (*gll_iem_v02.fits* & *isotropic_iem_v02.txt*), and the bright point sources within the ROI are first fitted (in flux) for each individual energy bin. We chose a symmetric Gaussian as the extended model for the source. The centroid and width of the Gaussian are iterated until the maximum likelihood is achieved. The analysis is performed using the ideal-case response point spread function (*P6_V3_DIFFUSE*) and also the worst-case counterpart (In-Flight fitted), and the average is taken. The best-fit for the whole energy band is found to be (l, b) = (189.05°, 3.03°) ± 0.01° (stat) ± 0.02° (sys) and $\theta_{68}^{extension}$ (°) = 0.27° ± 0.01° (stat) ± 0.03° (sys), which is consistent within error with the *EGRET* observation, but not with the hard X-ray PWN position (e.g. Gaensler et al. 2006). We are also interested in the displacement of the emission region as a function of energy, we hence further divide the band into two at 5 GeV and repeat the fitting procedure. The results are summarized in Table 2. A shift in centroid towards the *MAGIC*/*VERITAS* source positions with increasing energy is observed. Spatial relations between the Fermi measurement and other missions is shown in Fig. 2.

Spectral Analysis – We divide the 200 MeV – 50 GeV energy band into 13 log-uniform bins and perform a binned-likelihood spectral fitting using the standard *GTLIKE* analysis tool. A spatial template is first created for the IC 443 component in accordance with the best-fit Gaussian obtained in the spatial analysis. We attempted two different spectral models for the IC 443 component – a simple power-law and a broken power-law. The fit results are tabulated in Table 3. A broken power-law with spectral indices of ~ 1.9 and 2.6 with an energy break at around 3.3 GeV is found to represent the photon spectrum of IC 443 reasonably well, with a reduced chi-square of 0.99. A simple power-law gives a poor fit. This conclusion is cross-checked with an independent spectral fit using '*Sourcelike*', which yields consistent results. Fluxes at each energy bin are determined using a bin-by-bin, model-independent method. When plotted jointly with *EGRET*, *MAGIC* and *VERITAS* measurements, the broadband spectral energy distribution (SED) shows a consistent shape with a smooth roll-over at around 3 GeV (Fig. 3). This spectrum exceedingly resembles a gamma-ray spectrum of pion-decay origin. In fact, the SED can be fitted amazingly well with a purely pionic component, originated from protons with a broken power-law spectrum with indices of **2.1** and **2.9** and an energy break at **69 GeV** (black solid line in Fig. 3). Assuming an interacting gas mass of $10^4 M_\odot$ (Torres et al. 2008), a gas volume of 2×10^{59} cm³ and a distance of 1.5 kpc (Fesen 1984), then the total isotropic luminosity L(>200 MeV) of IC 443 is **1.22×10^{35} erg/s** and the total energy W_p(>100 MeV) of the protons is ~ **9×10^{49} erg** (~ 110 times the flux level of the diffuse cosmic ray protons at 10 GeV). Alternative models including bremsstrahlung and inverse compton scattering cannot explain the observed high gamma-ray flux in this energy range if the local e/p ratio is ~ 0.01 and the seed photon density mainly comes from the CMB. Bremsstrahlung can however become important below 200 MeV. More constraints can be obtained when improved measurements and calibrations for lower energy gamma-ray photons become available.

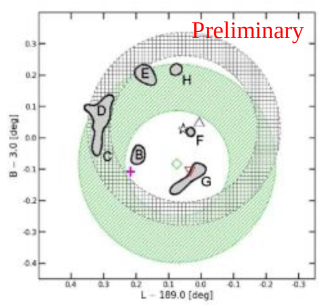

Fig. 2 – Centroids and extensions of sources: PWN (+), *EGRET* (△), *MAGIC* (▽), *VERITAS* (◇) with extension (θ_{68}) (green band with 1σ error width) and *Fermi* (star) with extension (θ_{68}) (grey band with 1σ error width). Contours show locations of shocked molecular clouds (Huang et al. 1986).

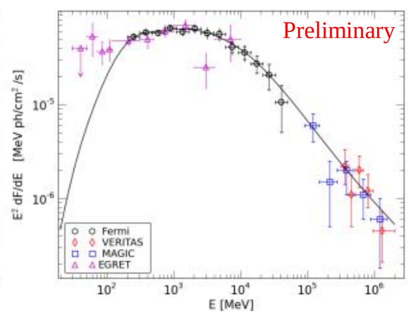

Fig. 3 – Measured gamma-ray SED of IC 443. Capped and uncapped error bars on Fermi points represent statistical and systematic errors respectively. Black solid line shows an attempt of spectral fit using a purely pionic component with a broken power-law proton spectrum (see text).

Conclusion –

- IC 443 is detected at ~ 86 σ level in the 200 MeV – 50 GeV energy range
- IC 443 is an extended source for LAT with $TS_{extension}$ ~ +300 (> 17 σ) against a point-source hypothesis. θ_{68} is estimated to be 0.27° ± 0.01° (stat) ± 0.03° (sys), which remains unaltered within the current energy band. The extended region overlaps well with the *VERITAS* source.
- Measured centroid of IC 443 is (l, b) = (189.05°, 3.03°) ± 0.01° (stat) ± 0.02° (sys), which shifts at 1 – 1.5σ level from < 5 GeV to > 5GeV. Location is inconsistent with the PWN location, and displaces 5 and 1.5 × θ_{68} away from the *MAGIC* and *VERITAS* centroids respectively, but is consistent within errors with the *EGRET* source.
- Measured photon SED is represented well by a broken power-law with a energy break at 3.25 ± 0.60 GeV. The *Fermi* flux points blends well with other measurements to reveal a smooth rolling-over gamma-ray spectrum of IC 443. The MeV–TeV SED can be satisfactorily reproduced by a purely pionic component with a broken power-law proton spectrum breaking at ~ 70 GeV, except for E < 200 MeV where bremsstrahlung may contribute.
- Higher statistics is required to establish association or non-association with molecular clouds and/or the PWN., which is definitely achievable by *Fermi* as data accumulates.