Resolving the Hadronic Accelerator IC 443:
A Joint Study with Fermi-LAT and VERITAS

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6th Fermi Symposium, Nov. 11, 2015
IC 443: Interacting with a Multi-Phase ISM

- Evolved (radiative) SNR interacting with a molecular cloud

WISE 3-color IR image of shocked dust

Radio 20cm

Schematic of IC 443 from Lee, et al. (2008)
IC 443: Prominent γ-ray Supernova Remnant

- GeV γ rays detected by EGRET in 90’s. TeV γ rays detected by MAGIC, VERITAS
- Spatially extended in GeV/TeV γ rays
- Later AGILE, Fermi-LAT detect π⁰ bump (e.g. Abdo, et al. 2012)

(Note: Images always oriented in J2000)
Our Improving $\gamma$ ray Views

**Fermi LAT** 2010: 13 mos. P6V3 data
**VERITAS** 2007: 38hrs

**VERITAS** 2007: 38hrs → 2015: 178hrs + PMT upgrade, T1 move

IC 443 is resolved as a γ-ray shell SNR

Counts Map >5 GeV (PSF23)  
Significance Map
Utilizing PSF Event Types in Pass 8

**LAT** morphology compared to **TeV** - **VERITAS** contours at 3, 6, 9, 12 \(\sigma\)

Counts Map >5 GeV (PSF23)

See Sajan Kumar’s poster (SNR 5) for **VERITAS** details
Utilizing PSF Event Types in Pass 8

**LAT** morphology compared to TeV, **radio** - 327 MHz continuum

Counts Map >5 GeV (PSF23)
Utilizing PSF Event Types in Pass 8

**LAT** morphology compared to TeV, radio, ambient CO

Counts Map >5 GeV (PSF23)
Utilizing PSF Event Types in Pass 8

**LAT** morphology compared to TeV, radio, ambient CO, shocked HCO+

Counts Map >5 GeV (PSF23)
Multi-wavelength comparison shows the GeV/TeV γ rays match the distribution of shocked gas in IC 443

**LAT** morphology compared to TeV, radio, ambient CO, shocked HCO+

Counts Map >5 GeV (PSF23) ~$10^4 M_{\odot}$ of shocked gas along southern ridge (Lee, et al. 2008)
• Multi-wavelength comparison shows the GeV/TeV $\gamma$ rays match the distribution of shocked gas in IC 443

**LAT** morphology compared to TeV, radio, ambient CO, shocked HCO+ shocked atomic gas in North?

HI absorption $\rightarrow 40\pm4$ M$_{\odot}$
(Castelletti, et al. 2011)

H$^+$ gas has $n_e=10$-1000 cm$^{-3}$
(Rho, et al. 2001)
• Lucy-Richardson deconvolution with wavelet denoising enhances spatial structures (as done previously with W44; Abdo et al. 2010)

Deconvolved 1–300 GeV events. Pass 8 gives 2.4x statistics of P7REP with cut on PSF68 < 0.4°

• Deconvolved LAT image is used as an extended spatial template to isolate different emission regions

see arXiv:0705.1362
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Exploring 4 Distinct Regions

Extract spectra from distinct regions using 4 spatial templates for LAT / circular apertures for VERITAS
Exploring 4 Distinct Regions

Region 1

Region 2

PRELIMINARY
Exploring 4 Distinct Regions

Region 1

Region 2

Region 3

PRELIMINARY

Graph showing energy distribution with energy on the x-axis and $E^2 dN/dE$ on the y-axis.
Exploring 4 Distinct Regions

Region 1
Region 2
Region 3
Region 4

PRELIMINARY

$E^{-2} \, dN/dE \, [\text{erg cm}^{-2} \, \text{s}^{-1}]$

Energy [MeV]

$10^{-14}$ $10^{-13}$ $10^{-12}$ $10^{-11}$ $10^{-10}$ $10^{-9}$ $10^{-8}$ $10^{-7}$ $10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$
Exploring 4 Distinct Regions

- No clear differences in spectral shape for distinct emission regions (e.g. dense cloud in region 1 vs. fast atomic shock in region 4)

Broken PL fits for all 4 regions:
\( \Gamma_1 \sim 2.3, \Gamma_2 \sim 2.9, E_b \sim 60 \text{ GeV} \)

Note: Uncertainties in the absolute flux calibration between Fermi LAT and VERITAS are NOT considered here
Comparing Regions: GeV vs TeV fluxes

- TeV/GeV integral flux ratios are consistent within errors between all 4 regions, despite ~10x change in brightness

$E^2 \frac{dN}{dE} \text{[erg cm}^{-2} \text{s}^{-1}]$ flux ratios of the 1-200 GeV and 0.2-6 TeV energy ranges
Comparing Regions: GeV flux vs Gas Mass

- Ratio of flux to gas mass shows significant differences between the dense molecular (1,2,3) and diffuse atomic (4) regions

\[ M_Y \sim 2,500 \ M_{\odot} \] can explain \( \zeta_{CR} \sim 2 \times 10^{-15} \) from \( \text{H}_3^+ \) (Indriolo, et al. 2008)
• *Fermi* LAT Pass 8 data resolves γ-ray shell from IC 443 in agreement with deep VERITAS observations

• Able to resolve γ-ray emission zones on ~5 pc scales in IC 443

• GeV/TeV correspondence with shock interaction gas density

• Spectra of all 4 regions show consistency with same broken power law

• *Data are still statistics limited…*
Backup Slides
**Fermi LAT** extension fit in 6 distinct energy bins from 0.3-1,000 GeV
Two nearby molecular clouds

- Foreground molecular cloud cuts across SNR. RGB image shows $v_{\text{LSR}} = -2, -4, -6$ km/s against Radio contours

- +5 km/s cloud ends at TeV peak

![Image 1: Foreground molecular cloud cuts across SNR.](image1)

![Image 2: +5 km/s cloud ends at TeV peak.](image2)

**Figure 15.** Far-IR 90 $\mu$m image taken with the AKARI satellite shown in gray scale. The green contours show the distribution of +5 km s$^{-1}$ clouds (the gray scale in Figure 9). The blue contours show locations of SCs. The solid and dashed circles represent the location of $\gamma$-ray sources detected by MAGIC and VERITAS, respectively.

Figures from Lee+ 2008
Image Restoration Technique

Richardson-Lucy Deconvolution Algorithm

- When we observe an event at position \( x \)
  - \( P(x: \xi) \): probability that it came from a “true” position \( \xi \) due to instrument response

\[
\psi^{r+1}(\xi) = \int \tilde{\phi}(x) \frac{\psi^r(\xi)P(x: \xi)}{\int P(x: \zeta)\psi^r(\zeta)d\zeta} dx
\]

Lucy 1974
Richardson 1974

Generalization to Event-by-event \( P_k(x: \xi) \)

\[
\psi^{r+1}(\xi) = \frac{1}{N} \psi^r(\xi) \sum_{k=1}^{N} \frac{P_k(x_k: \xi)}{\int P_k(x_k: \zeta)\psi^r(\zeta)d\zeta}
\]

- Can be used for event-by-event data with varying PSF.
- No energy spectrum assumption necessary

- Point sources can be incorporated using dual-channel method

\[
\psi = \psi_{\text{point}} + \psi_{\text{extended}}
\]

Hook&Lucy 1994
Wavelet Denoising

- Minimize the effect of Poisson noise
  » Wavelet filtering technique

\[ \psi_n \rightarrow \phi^n = P \psi^n \rightarrow R^n \rightarrow \text{FILTER} \rightarrow R'^n \rightarrow \phi' \rightarrow \text{RL} \rightarrow \psi^{n+1} \]

\[ \phi \]: observed image
\[ R^n = \phi - \phi^n, \quad \phi' = R'^n + \phi^n \]

\[ \psi = \sum_{j=0}^{n} w_j + c_n \]

Starck&Murtagh 1994