Connecting $\gamma$-ray Emission from SNRs To Galactic CRs

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Highlight Talk
Synergies:

\( \gamma \)-rays provide a unique perspective on cosmic ray astrophysics:
- via direct and indirect detection techniques
- to address CR origins, acceleration, and propagation.

Indirect CR evidence:
- potential sources: MW studies using spatial and spectral information give insight into particle populations and acceleration processes
- can depend on environment…
- Use environment as CR “calorimeter” to infer CR distributions beyond Earth. Studies of diffuse \( \gamma \)-rays give insight into CR propagation.

Direct CR detection: In addition to the many experiments here!
- CRs are the background for all \( \gamma \)-ray experiments: collect and analyze data!
- Use particle shower techniques, Earth’s B-field, etc for charge separation.
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CR measurements provide insight into the sources best investigated in γ-rays.
Indirect Detection:

Image potential sources of galactic CRs to determine:
- their acceleration processes
- the composition of accelerated particles and thus,
- their ability to produce high energy particles with the observed galactic CR properties…

γ-rays (and Fermi in particular)
- Good image resolution ⇒ spatial separation of the components
- Sensitivity to pion decay products ($\pi^0 \rightarrow \gamma \gamma$)
  - and bremsstrahlung & inverse Compton processes
  - ⇒ spectral separation of acceleration processes
- Survey mode gives high statistics.
- In combination with full E-M spectrum and spectroscopy, can begin to resolve potential sources’ ability to accelerate CRs.

Individual SNRs → a catalog of SNRs
  → statistically significant observations about the population!
Fermi Gamma-ray Space Telescope

Photon Detector

Launched: 11 June 2008 on a Delta II rocket

Photon Energy and Direction

from 2 main (science) subsystems:

- **GBM:** Gamma-ray Burst Monitor
  - 12 NaI detectors: 8 keV – 1 MeV
  - 2 BGO detectors: 0.15 – 30 MeV
  - nearly full sky coverage at all times
- **LAT:** Large Area Telescope
Fermi Gamma-ray Space Telescope

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- **LAT:** Large Area Telescope
  - **Tracker:** 4x4 array of towers, each with 18 planes of Si-strip detectors interleaved with W converting foils
  - **Calorimeter - E:** 8 layers of 12 CsI(Tl) crystals oriented orthogonally
  - **ACD - CR veto:** tiled plastic scintillator
Fermi Detected $\gamma$–ray Emission

Data:
- 4yrs’ exposure
- P7v6
- Front events
- $E>1\text{GeV}$
13 identified SNRs, including
- 9 interacting
- 4 young SNRs
Fermi-Detected $\gamma$–ray SNRs

13 identified SNRs, including
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+ 43 2FGL candidates,
excluding identified PSRs, PWN, AGN
Fermi-Detected $\gamma$–ray SNRs

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CTB 37A

Detection: Fermi-LAT data shows non-variable emission from a region coincident with the MW SNR.

Spectral study: MW model fitting shows emission is best-fit with $\pi^0$-decay + bremsstrahlung.

Energetics: ~5% of the energy goes into (hadronic) CRs.

Particle populations’ and environment constraints:
- Particle power laws: flux, index, (lepton) cutoff $E$
- B-field: first lower limit, constraining UL
S. Abdollahi’s talk!

Detectic and studies MSH 15-52 and Vela Jr. w HESS, from a r Cas A and γ-Cygni w MAGIC+, etc

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Indirect: Potential Sources

Detection of low energy $\pi^0$-decay cutoff in 3 SNRs’ spectra suggests proton acceleration:
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**Indirect: Potential Sources**

W51C: 3rd SNR w evidence of $\pi^0$ bump

Maximum Energy??

Ackermann et al. 2012
To better understand SNRs in a statistically significant manner, within a MW context.

- Systematically characterize GeV emission in regions containing SNRs,
- Identify and determine the characteristics of the GeV SNR population,
- Examine multiwavelength (MW) correlation(s),
- Constrain known SNRs’ contribution(s) to the Galactic CR population

With particular efforts from:
F. Acero, J. Ballet (CEA-Saclay/France)
T. J. Brandt*, J. Cohen (NASA/Goddard)
F. de Palma* (INFN/Bari), J. W. Hewitt* (U. N Florida)
G. Johannesson (U. Iceland), M. Renaud (LUPM),
L. Tibaldo (SLAC), B. Wells (UCSC)
*contact authors
Characterize GeV Emission: Analysis Procedure

Data Set:
- 3 years of P7SOURCE_V6 LAT data
- E: 1-100 GeV
- Region Of Interest: 10° around each SNR

Green’s Catalog: (2009)
- 279 SNRs

Starting Model:
- 2FGL

Overlapping sources?
- = None: Add a new extended source
- = 1 source (not PSR): Replace w extended source
- > 1 source: Replace (non-PSR) source closest to radio centroid w extended source. Delete all other (non-PSR) sources.

Localize source, fit extension
- Disk extension seed = radio size
- Spectral model: power law, log parabola
- Effect of nearby sources
- Normalization of Galactic diffuse and all sources w/in 5° of candidate are free

Characterize the systematic error from the interstellar emission model and effective area

Improve starting model: AddSources

Identify candidates as likely SNRs via spatial coincidence.

Output:
- Significance, position, extension
- Spectral energy distribution
- Region and residual maps
- Diagnostics
SNR Catalog: Results!

Characterized 279 regions containing known radio SNRs:

- 102 candidates have significant GeV emission:
  - 30 candidates pass classification threshold and are likely SNRs: (location and extension overlap fractions ≥0.4)
    - 17 extended: 4 new!
    - 13 point hypothesis preferred: 10 new!
    - 2 have logP spectra (in 1-100GeV energy range)
  - 14 marginally classified as SNRs including
    - 2 candidates were demoted from classified to marginally classified due to their behavior under the systematic errors
- 54 other GeV sources within 3° of an SNR
  - 4 identified as not SNRs (Crab, binary, and PWN/PSR)
- 245 flux upper limits at radio position and extension
  - All marginally classified and other candidates
  - for those which are significant but don’t pass classification, both candidate parameters and radio SNR UL reported
Characterize GeV emission in regions containing known SNRs:

- Green's 2009 catalog:
  - 279 regions
- Improve 2FGL starKng model within 3° using AddSrcs (uses pointlike):
- retain PSRs, AGN
- test source at max in TS map: localize, spectral curvature
- stop: TS global ≤ 16 for 3 consecutively added sources
- Use pointlike tool to localize source, test for extension, and determine impact of nearby source(s)
- Perform spectral fit for significant sources and test for spectral curvature using gtlike.
- Estimate the impact of choice of interstellar emission model (IEM):
  - run pipeline from localization step using 8 alternative IEMs
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SNR Catalog: Classified + Marginal Candidates
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- Perform spectral fit for significant sources and test for spectral curvature using gtlke.

- Estimate the impact of choice of interstellar emission model (IEM):
  - rerun pipeline from localization step using 8 alternative IEMs

SNR Catalog: ...+ Other Sources
SNR Catalog: Spectra

Classified: Young, Interacting

$E^2 \frac{dN}{dE} \text{[MeV}^{-1} \text{s}^{-1} \text{cm}^{-2}]$ vs. Energy [MeV]

- ○ Extended
- ● Pointlike
SNR Catalog: Spectra

Marginal: Young, Interacting
SNR Catalog: Spectra

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Other Sources

\[ E^2 \frac{d^2 N}{dE} \text{[MeV s}^{-1} \text{cm}^{-2}] \]

\[ \text{Energy [MeV]} \]

\[ \text{Extended} \]

\[ \text{Pointlike} \]
Classified GeV candidates tend to correlate with their radio size, particularly for larger diameters with lower systematic errors:

- Interacting SNRs: density $\geq 100 \text{cm}^{-3}$
- Young SNRs: evidence of non-thermal X-ray emission
- Classified candidates
- Marginal candidates
- Capped error bars: Statistical
- Uncapped: Systematic
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+ More than 100 GeV sources within 3° of a known SNR!

\( \phi \) = limit on GeV size imposed by classification
Candidates span 2 orders of magnitude in flux and from ~1 – 5 in index, despite examining only 1-100 GeV energy range.

- **Interacting SNRs:** density $\geq 100\text{cm}^{-3}$
- **Young SNRs:** evidence of non-thermal X-ray emission
- **Classified candidates**
- **Marginal candidates**

- **Capped error bars:**
  - Statistical
- **Uncapped:** Systematic
Radio synchrotron emission indicates the presence of relativistic leptons. LAT-detected SNRs tend to be radio-bright:

- **Interacting SNRs:** general correlation?
- **Young** SNRs show more scatter
- **Applied Kendall τ test:** no deviation from non-correlation of radio-GeV flux for any class

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**Radio-GeV Correlation?**

![Graph showing correlation between Flux(1 GHz) and Flux(1 GeV)]

- **Extended**
- **Pointlike**
- **Classified**
- **Marginal**
- **Upper Limits** (i=2.5, 99%)
- **ULs, interacting** (i=2.5, 99%)
- **ULs, young** (i=2.5, 99%)
Radio-GeV Index

If radio and GeV emission arise from the same particle population(s), under simple assumptions, the GeV and radio indices should be correlated:

- **Young SNRs**: seem consistent
- **Others, including interacting SNRs**: softer than expected

Data now challenge model assumptions!
- Underlying particle populations may have different indices.
- Emitting particle populations may not follow a power law; breaks?
- Multiple emission zones?
GeV-TeV Index

- Indication of break at TeV energies
- Caveat: TeV sources are not uniformly surveyed.
GeV-TeV Index

- Indication of break between GeV and TeV
- Caveat: TeV sources are not uniformly surveyed.

RX J1713-3946 SED

Fermi

IACT

E^2 dN/dE

1 GeV

1 TeV

Break region

Extended

Pointlike

Classified

Marginal
Young SNRs tend to be harder than older, interacting SNRs.

GeV index evolves w time:
- apparent increase for older remnants

May be due to a combination of:
- decreasing shock speed allowing greater particle escape
- decreasing maximum acceleration energy as SNRs age
We can relate our SNR flux measurements to the energy imparted to CRs:

\[ F(1 - 100 \text{GeV}) \approx f(\Gamma_{CR}) \times \frac{\varepsilon_{CR}}{0.01} \times \frac{E_{SN}}{10^{51}\text{ergs}} \times \frac{n}{1\text{ cm}^{-3}} \times \left(\frac{d}{1\text{ kpc}}\right)^{-2} 10^{-9} \text{ cm}^{-2}\text{s}^{-1} \]

\( \varepsilon_{CR} \Rightarrow \) energy content in particles accelerated up to the observation time relative to the SN explosion energy.
If energy losses & escape negligible, \( \varepsilon_{CR} = \) hadron efficiency.
Constraining CR Acceleration

We can relate our SNR flux measurements to the energy imparted to CRs:

\[
F(1-100 \text{ GeV}) \approx f(\Gamma_{\text{CR}}) \times \frac{\varepsilon_{\text{CR}}}{0.01} \times \frac{E_{\text{SN}}}{10^{51} \text{ ergs}} \times \frac{n}{1 \text{ cm}^{-3}} \times \left( \frac{d}{1 \text{ kpc}} \right)^{-2} 10^{-9} \text{ cm}^{-2} \text{s}^{-1}
\]

where we take:

- photon index $\Gamma_{\text{GeV}}$ as a proxy for the CR index $\Gamma_{\text{CR}}$ and
- $f(\Gamma_{\text{CR}}) \sim \text{constant for } E_{\text{CR,max}} > \text{~200 GeV}$

1-100 GeV flux for a given $E_{\text{CR,max}}$ energy:

$\varepsilon_{\text{CR}} \Rightarrow \text{energy content in particles accelerated up to the observation time relative to the SN explosion energy.}$

If energy losses & escape negligible, $\varepsilon_{\text{CR}} = \text{hadron efficiency}$.

\[
\Phi = \frac{E_{\text{SN}}}{10^{51} \text{ ergs}} \times \frac{n}{1 \text{ cm}^{-3}} \times \left( \frac{d}{1 \text{ kpc}} \right)^{-2} 10^{-9} \text{ cm}^{-2} \text{s}^{-1}
\]
Constraining CR Acceleration

Estimates of and upper limits on the CR energy content span more than 3 orders of magnitude:

- SNRs with $\varepsilon_{\text{CR}} > 1$ ($E_{\text{CR}} \equiv E_{\text{SN}} \equiv 10^{51}$ erg) => higher density than derived from X-ray or assumed => interacting SNRs are in a dense environment.
- Young SNRs $\varepsilon_{\text{CR}} \sim 0.1 - 1.0$ => IC processes may contribute to their measured luminosity
HEAO-C2/TIGER & SuperTIGER Results

- **Refractory**: found in interstellar dust
- **Volatile**: low boiling point

CR Source:
- ~ 20% massive star ejecta
- ~ 80% solar system

Acceleration:
- More efficient for refractories than volatiles
- Mass-dependent:
  - refractory \( \sim A^{2/3} \)
  - volatile \( \sim A^1 \)

See talks including from J. Link, A. Labrador, N. Walsh, R. Mewaldt!

Graph showing the distribution of elements with atomic mass, with markers for SuperTIGER refractory, SuperTIGER volatile, TIGER/HEAO refractory, and TIGER/HEAO volatile. The graph includes data points for elements like Mg, Si, P, Al, Ca, Fe, Sr, Mg, Si, S, N, Ne, Ar, Ga, Zn, Se, Ge, and Ni.
Westerlund 1

Massive stellar cluster ~5kpc from Earth
Site of significant CR acceleration... ?

HESS (black contours)
★ new extended source
★ optical Wd1 position
+ pulsars
+ 2FGL sources

100 MeV - 300 GeV

6yrs P8 data
Westerlund 1

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• logL calculations
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3-300 GeV 100 MeV - 300 GeV

Extension at Maximum Likelihood Position

Preliminary

logL(0.85°)-logL(0.65°)=19.5 ≈ 6.2σ

=> Significant morphology change

logL(339.62°)-logL(339.72°)=0.73 ≈ 1.2σ

=> No significant position change
Westerlund 1

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Westerlund 1

Massive stellar cluster ~5 kpc from Earth
Site of significant CR acceleration... ?

- HESS (black contours)
- ★ new extended source
- ★ optical Wd1 position
- + pulsars
- + 2FGL sources
Indirect: Diffuse Studies

Study propagation around sources:

W44:
Particle escape? Shocked cloud?

See eg T. Joubaud’s poster on Orion-Eridanus Superbubble!

Use MW observations to find new sources!

Cocoon of 10-100 GeV $\gamma$-ray emission
IR emission from Cygnus Superbubble

Fermi-LAT SNR Catalog has >100 GeV sources detected within 3° of a known SNR…

Credit: I. A. Grenier (Fermi LAT/AIM/U. Paris Diderot/CEA) and L. Tibaldo (Fermi LAT/SLAC).
Indirect: Diffuse Studies

Infer CR propagation using High and Medium Velocity Clouds:

- Local Low-latitude IV Arch Complex A
- Local Lower IV Arch
- Upper IV Arch
- Local IV Spur

Emissivity = $\gamma$-ray emission rate / H atom

$z =$ height above Galactic plane

- $\gamma$-ray emissivity decreases as a function of distance from Galactic disk
- First direct corroboration of CR acceleration in disk and propagation into halo
- Complex A upper limit: currently most stringent constraint on CR flux at $z \sim$ few kpc.

Tibaldo, et al. 2015
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T. Mizuno’s talk on MBM 53-55 Clouds and Pegasus Loop!

T. J. Brandt
More Catalog Studies!

3rd Catalog of Hard Fermi-LAT Sources (3FHL): >10GeV

See A. Dominguez’s talk!

N. Park’s talk on Fermi+VERITAS observations of 2nd HAWC Catalog!
More Catalog Studies!

3rd Catalog of Hard Fermi-LAT Sources (3FHL): >10GeV  See A. Dominguez’s talk!

Fermi Galactic Extended Source Catalog (FGES):

- 10GeV - 2 TeV
- 46 extended sources
- 16 new extended sources: 8 not confused: 3 SNRs, Wd2, 1 unknown

M. Wood’s talk on Fermi extended sources at high latitude!

Ackermann, et al. 2017
More Catalog Studies!

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And studies, such as the HESS Galactic plane survey, HAWC studies, etc!

Ackermann, et al. 2017
More Catalog Studies!

3rd Catalog of Hard Fermi-LAT Sources (3FHL): >10GeV

- Fermi Galactic Extended Source Catalog (FGES): 1-100 GeV
- Multiple specialized Interstellar Emission Models (IEMs) with self-consistent point source determination
- 48 point sources, >5 coincident with SNRs

First Fermi-LAT Inner Galaxy Point Source Catalog (1FIG):
- 1-100 GeV
- Filled circles: 1FIG
- Angled crosses: TS<25 candidates
- Upright crosses: 3FGL MW associated sources
- Inverted triangles: Green’s catalog SNRs within 1FIG 95% error
- Upright triangles: ATNF pulsars within 1FIG 95% error x3

T. J. Brandt
More Catalog Studies!

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Fermi Galactic Extended Source

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IEMs improving! See talks by T. Porter, G. Johannesson

T. J. Brandt

Direct: Hadrons

Fermi-LAT proton measurement:

- $E > 20 \text{GeV}$
- 3 month’s data
- Above atmosphere…

See D. Green’s talk!
and M. Meehan’s talk on Fermi’s proton anisotropy!
Conclusions

We can use $\gamma$-rays to gain insight into CR origins, acceleration, and propagation via direct and indirect detection techniques.

Potential sources: SNRs, Massive star associations, PWNe, PSRs, …
- Combine spatial and spectral $\gamma$-ray information with MW observations
- infer the underlying particle populations, acceleration mechanisms, and emission processes,
- using improved theoretical models
- systematically for a statistically significant population of sources.
- Study shock dynamics/escape via nearby sources.
- Use MW data to find/identify new sources!

Propagation:
- Use clouds as CR “calorimeter” to infer CR distributions beyond Earth.
- H&IVCs and also Orion-Eridanus Superbubble, MBM 53-55 and Pegasus Loop, L & SMC, …

Direct CR measurements:
- constrain sources, locations, and propagation.
- Measurement with different techniques helps reduce impact of systematic error!

By diversifying and expanding our multimessenger CR studies, we will obtain the most profound insights in CR astrophysics.

PaMELA + AMS + ISS-CREAM + SuperTIGER + CALET + ACE + HELIX + DAMPE + NUCLEON + HNX + HAWC + Fermi + AGILE + VERITAS + MAGIC + HESS + CTA + NuSTAR + Chandra + XMM + IR + $\mu$wave + radio + IceCube + distances + …

=> CR origins, acceleration, propagation!

T. J. Brandt
Classification

Quantify spatial overlap:
Classification

Use measure of chance coincidence in mock catalog to estimate false discovery rate and error. Set thresholds to 0.4: <22% false discovery rate
Classification

Quantify spatial overlap:

[Graph showing spatial overlap with labeled axes and legend for classified, marginally classified, and other candidates.]
Potential sources must accelerate hadrons.

Necessary but not sufficient!

… up to $\sim 10^{15}\text{eV}$
(if knee $\leftrightarrow$ end of Galactic CRs)

SNRs: Most likely largest contributors of energetic particles sculpting galaxies.

W51C: 3rd SNR w evidence of pion bump

W44, IC443, W51C: all older remnants interacting w significant nearby material.
Morphology: Escape/Acceleration?

Discovering new sources in close proximity to SNRs! Often coincident with clouds. Evidence of CRs escaping and illuminating the clouds? Or the shock front crushing the clouds, reaccelerating CRs / accelerating new CRs?

Example: W44

CRs’ escape? Shocked cloud?

To understand the quality of our analysis using the most accurate methods to date, we refit for all quantities, including extension and best final hypothesis with eight alternative interstellar emission models (IEMs):

**Systematic Errors**

Significant Source:

Extension Hypothesis:
Systematic Errors

We estimate the GeV systematic errors using the alternative IEMs and the effective area bracketing IRFs, summing the independent errors in quadrature.
Flux v Radio Size

No clear correlation nor separation between classes:

Candidates tend to:
- span the range of known sizes
- fill in regions with previously fewer known sources =>
- ability to make more statistically robust population statements!

1-100 GeV Flux [ph cm\(^{-2}\) s\(^{-1}\)]

Radio Diameter [deg]
Luminosity v Physical Radio Size

No clear trend though both axes are proportional to distance$^2$. Some separation between classes, diminishing as we find more, less luminous candidates: