Galactic Science: from *Fermi*-LAT to CTA

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*Gamma Ray Astrophysics with CTA*

*Sexten 2017*
Outline

• Overview of Galactic sources
  – Pulsars
  – Pulsar Wind Nebulae
  – Binaries
  – Novae

• LAT SNR observations

• Catalogs

• Prospect for CTA Galactic science

• Conclusions
What does Fermi see of our Galaxy?

Galactic sources:

- **Pulsars**
- **PWNe**
- **Novae**
- **Binary systems**
- **SNRs**
- Galactic center and interstellar emission
- **Solar System**

3FGL Catalog: 3033 sources
6% are PSR and 5% other Galactic sources
Now up to 205 $\gamma$-ray pulsars!

Current public gamma-ray pulsar list: http://tinyurl.com/fermipulsars

Credit: T. Johnson
Pulsar classes

Young (not recycled)

MSP (recycled)

https://arxiv.org/abs/1706.03592
Pulsar Wind Nebulae

• Energy is carried away in a magnetized wind of charged particles.
• PWNe contain both the relic accelerated particles from the pulsar and particles accelerated within the termination shock.
Crab not a standard candle

Also detected by Agile: Tavani+ Science 2011
Binary systems with $\gamma$-ray variability

**Microquasars: Cygnus X-3**

- BH or NS in binary systems with relativistic jets
- Identified by:
  - Location;
  - modulation of the $\gamma$-ray flux at the orbital period of the binary system;
  - $\gamma$-ray variability correlated with the radio emission.

**Pulsar Binaries: PSR B1259-63**

- Emission due to the interaction of the relativistic PSR wind and the photon field of the massive star.
- Periodicity: 3.4 years

Also detected by Agile: Tavani+ Nature 2009
γ-ray Novae

- 6 Novae detected up to now (ongoing researches on new candidates)
- Soft spectrum transient γ-ray sources detected over 2–7 weeks.
- Unexpected high-energy particle acceleration processes linked to the mass ejection from thermonuclear explosions.

Abdo+ Science 2010
Ackermann+ Science 2014
Cheung+ Apj 2016
Supernova Remnants

NASA’s Fermi telescope resolves supernova remnants at GeV energies

Cas A  W51C  W44  IC 443
SNRs with hadronic emission

M. Ackermann+ 2013 (detected also by AGILE: Giuliani+ 2011)


HESS + Fermi-LAT
Accepted for publication in A&A
Young SNRs

- Approx. few thousands years old
- Simple environments
- Small energy losses

Ideal targets to test the acceleration theory and look for ‘Pevatrons’

Leptonic scenario

RX J1713.7-3946

RCW 86

\( \gamma \)-ray emission dominated by Inverse Compton

B. Condon+ @ Gamma 2016

Young SNRs

Hadronic scenario

Cassiopeia A

Leptonic

Hadronic

Also in: M. L. Ahnen+ 2017 Submitted

Tycho

γ-ray emission dominated by pion decay
Presence of accelerated protons

F. Giordano+ ApJL 2012
Also in: S. Archambault 2017 Accepted by ApJ
Morphology studies with Pass 8

RCW 86

Detected as extended with Pass8:
radius $\sim 0.37^\circ \pm 0.02^\circ$

Best morphological photon distribution: **H.E.S.S. template**
(A. Abramowski+,
accepted for publication by A&A)

**Multi-zone analysis ongoing**

**IC 443**
Preliminary results in
Hewitt+ @ Fermi Symposium 2015

Improved spatial correlation with TeV template (Aharonian + 2006)

3.5 σ significance of improvement using a split template

Condon, B+ @ Gamma 2016
• Energy dependent morphology
  – Clear trend toward the PWN at higher energies

• Harder and softer spectrum for the PWN and the SNR respectively

Devin, J+ @ SF2A 2017
3FHL identification & association

Data:
- Pass 8,
- 7 Years,
- $10 - 10^3$ GeV
- 1556 objects (8% Galactic)

Preliminary version:
Arxiv:1702.00664

Fits on the FSSC webpage:
gll_psch_v11.fit
• Study of extended sources in the Galactic plane
• Detected 46 extended sources:
  – 16 are new
  – 13 agree with previous publications
  – 17 have a different morphology.
  – Only 4 known LAT extended sources were not detected since they don’t have emission above 10 GeV

Preliminary version: Arxiv:1702.00476

Data:
• Pass 8,
• 6 Years,
• 10 GeV - 2 TeV
Sources modeled as flat disk
New extended sources in FGES: CTB109

- First detection of gamma-ray extension (point source in Castro+ 2012)
- Good agreement with x-ray/radio size
- Rules out giant molecular cloud west of remnant
- Good candidate for TeV observation
Energy dependence: W30 region

• Previous analysis starting at 2 GeV (Ajello+ 2012) correspond to radio structure while at above 10 GeV (FGES) it seems to correspond to TeV contours (HESS J1804-216, Aharonian+2006)

• Origin of the GeV TeV emission:
  – PWN, but it is unusually large spatial extent for a PWN, or
  – interaction of escaping CR with nearby MC
Characterized 279 regions containing known radio SNRs:

- 102 candidates have significant GeV emission:
  - 36 candidates classified through spatial association with radio data:
    - 17 extended: 4 new!
    - 2 show spectral curvature
    - 13 point-like hypothesis preferred: 10 new!
  - 2 are flagged for IEMs systematics
  - 4 identified as other sources (Crab, binary, and PWN/PSR)
  - 14 marginally classified candidates
- For the 245 candidates that don’t have a significant GeV emission or that fail classification, we report their ULs.
- All the detected sources were tested for effects related to the choice of IEMs. 
  
Acero+ 2016 APJS
Indexes of the candidate sources are distributed in the large range between 1.5 and 5, while fluxes are in a two orders of magnitude interval.

- **Interacting SNRs** density $\geq 100 \, cm^{-3}$
- **Young SNRs** show evidence of non-thermal X-ray emission
- **Classified candidates**
- **Marginal candidates**
- **Pointlike sources**
- **Extended sources**

- Capped error bars: statistical errors
- Uncapped: systematic uncertainties.
LAT-detected SNRs tend to be radio-bright:

- **Interacting SNRs**: general correlation?
- **Young SNRs** show more scatter

*Applied Kendall $\tau$ test*: no deviation from non-correlation for any (sub)set of candidates.
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

- \( \pi^0 \) decay or \( e^+/− \) brem.
- Inverse Compton \textit{w} cooling
- Inverse Compton \textit{w/o} cooling

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?
• Indication of break at TeV energies
• Caveat: TeV sources are not uniformly surveyed.
Indication of break at TeV energies
Caveat: TeV sources are not uniformly surveyed.
Constraining CR emission

Assuming that the whole gamma ray emission arises from the interaction of CR with the ISM.

\[ F(1 - 100 \text{ GeV}) \approx f(\Gamma_{CR}) \times \frac{e_{CR}}{0.01} \times \frac{E_{SN}}{10^{51} \text{ erg}} \times \frac{n}{1 \text{ cm}^{-3}} \times \left( \frac{d}{1 \text{ kpc}} \right)^{-2} \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1} \]
The estimates and upper limits on the CR energy content span more than three orders of magnitude, from a few $10^{49} \text{erg}$ to several $10^{52} \text{erg}$.

- SNRs above the $\epsilon_{CR} = 1 (E_{CR} = E_{SN} = 10^{51} \text{erg}) \rightarrow$ higher density than derived from X-ray or assumed $\rightarrow$ interacting SNRs are in dense environment.
- Young SNRs $\epsilon_{CR} \sim 0.1 \rightarrow$ IC processes may contribute to their measured luminosity.
H.E.S.S. source classification in the Galactic Plane survey

MWL counterparts:
- Pulsars (ATNF)
- PWN (SNRcat)
- SNRs (SNRcat)

Donath A.+, TeVPa 2016

See C. Van Eldik talk!
Very High Energy (VHE – 0.2-100 TeV) γ-ray image of the inner part of the Milky Way (l=65°-250°, |b|<3.5°) from the latest H.E.S.S. Galactic Plane Survey (HGPS).

Deil et al. 2015, **talk at the 34th ICRC**
CTA flux sensitivity

Major sensitivity improvement & wider energy range
• total dark time available for all CTA observations will be 1100–1300 h/year at each site.
• open, proposal-driven observatory
• for first 10 years 40% of the time is devoted to **key science programs (KSP)** run by the CTA consortium

The plot and tables in the next slides are from: *The CTA Consortium, Science with the Cherenkov Telescope Array*, to be submitted soon.

*See A. Giuliani talk!*
# Key Science Projects (KSP)

<table>
<thead>
<tr>
<th>Theme</th>
<th>Question</th>
<th>Galactic Plane Survey</th>
<th>Cosmic Ray PeVatrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Understanding the Origin and Role of Relativistic Cosmic Particles</td>
<td>1.1 What are the sites of high-energy particle acceleration in the universe?</td>
<td>✓ ✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>1.2 What are the mechanisms for cosmic particle acceleration?</td>
<td>✓</td>
<td>✓ ✓</td>
</tr>
<tr>
<td></td>
<td>1.3 What role do accelerated particles play in feedback on star formation and galaxy evolution?</td>
<td>✓ ✓</td>
<td>✓</td>
</tr>
<tr>
<td>Probing Extreme Environments</td>
<td>2.1 What physical processes are at work close to neutron stars and black holes?</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
</tr>
<tr>
<td></td>
<td>2.2 What are the characteristics of relativistic jets, winds and explosions?</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
</tr>
<tr>
<td></td>
<td>2.3 How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?</td>
<td>✓ ✓</td>
<td>✓ ✓</td>
</tr>
</tbody>
</table>
Simulated GPS

![Graph showing simulated GPS data.

Longitude (deg) | Latitude (deg)

-4 | 4
-3 | 4
-2 | 4
-1 | 4
0 | 4
1 | 4
2 | 4
3 | 4
4 | 4

26/07/2017
A total of 1020 and 600 hours for CTA-South and CTA-North, respectively.
Estimated number of target sources

From 1st approx. estimation ~ 100 new SNRs, hundreds of PWN, handful of binaries and few pulsars.

From R. Zanin ICRC2017
### Pevatron KSP

<table>
<thead>
<tr>
<th>Target</th>
<th>Type</th>
<th>Exposure (h)</th>
<th>Array</th>
<th>Year</th>
<th>Configuration</th>
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<tbody>
<tr>
<td>RX J1713.7–3946</td>
<td>SNR</td>
<td>50</td>
<td>S</td>
<td>1–3</td>
<td>Full array</td>
</tr>
<tr>
<td>PeVatrons</td>
<td>Unknown</td>
<td>5×50</td>
<td>S</td>
<td>&gt;3</td>
<td>MSTs + SSTs</td>
</tr>
</tbody>
</table>

![Graph showing energy spectra for different E_cut values](image)
Simulated morphologies for different emission mechanisms with 50h of observation.
Spectral studies

SNR RXJ1713.7-3946

Molecular cloud illuminated by cosmic rays coming from a nearby SNR at different distances
Conclusions

• Fermi has proved to be extremely successful in studying galactic sources, both steady and variable.
• Pass 8 is allowing detailed studies of the morphology of extended sources, better identifying emitting regions.
• Multiwavelength analysis allows to study the emission mechanism.
• In the SNR catalog we have identified a statistically significant population of Galactic SNRs, including:
  – 17 (4 new) extended and 13 (10 new) pointlike SNR candidates
• CTA observations of the Galactic plane will strongly improve our understanding of the Galactic high energy emission.
  – A strong increase of detected sources is expected
  – Spatial resolved spectroscopy will be possible given CTA high spatial and spectra resolution.