Fermi Observations of Pulsars and Pulsar Wind Nebulae

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on behalf of the
Fermi-LAT Collaboration
& the Pulsar Timing Consortium

– Searching for the sources of Galactic Cosmic rays,
Paris, France, 14 December 2012 –
A direct link between Pulsars and PWNe and Cosmic-Rays

Rotation powered neutron stars produce $e^+e^-$ pairs injected in ISM when out of Pulsar Wind Nebula

Pulsars are excellent antimatter factories!

PAMELA excess can be explained if average escape from SNR takes place $10^4$-$10^5$ years after SN

Hooper D., Blasi P., Serpico P., JCAP01(2009)025
Three ways to detect Pulsars with Fermi-LAT

1- Folding gamma-ray photons according to a known pulsar timing model, from radio or X-rays
   - All 6 EGRET pulsars were detected this way (but Geminga, Crab and Vela could have been discovered in blind searches; Ziegler 2008, Chandler et al. 2001)
   - LAT photons are now folded for 762 Pulsars thanks to the Fermi Pulsar Timing Consortium!

2- Blind searches for pulsations directly in the gamma-ray data
   - Spectacularly successful for young pulsars
   - Really hard for MSPs!

3- Radio pulsar searches of LAT unidentified sources
   - Sensitivity to MSPs, binaries, very noisy pulsars

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A growing population of LAT Pulsars

117 LAT-detected pulsars in 2PC

Credit: Paul Ray (Fermi Symposium)
Fermi Second Pulsar Catalog (2PC)

Spectra

Luminosities

Correlations

All data, including spectral and light curve points to be available online.
40 MSPs included in 2PC: Success!
NEW (not in 2PC): a blind search MSP!

Blind Search for MSPs extremely difficult: Pulsar parameters unknown + unknown orbital parameters (for binary system) => increase computational complexity by orders of magnitude

Initial target source: 2FGL J1311.7-3429, brightest unidentified steady source seen by LAT with very curved spectrum & in search for optical counterparts. Romani (2012) observed quasi sinusoidal optical flux modulation => conjecture: black widow pulsar binary

Successful detection of pulsed emission using a total of $10^{17}$ grid points ($10^8$ in $f$, $10^2$ in $\dot{f}$, $10^7$ in orb.)!
And some of these pulsars even emit gamma-rays above 10 GeV!

Fermi LAT Catalog above 10 GeV: nearly 3 years, 514 sources detected

Among them 27 pulsars are detected

Pulsations observed above 10 GeV for 11 (out of 27):

J0007+730 (CTA1), J0534+2200 (Crab), J0614-3329, J0633+174 (Geminga), J0835-4510 (Vela), J1028-5819, J1048-5832, J1709-4429, J1808-2332, J2021+3651 (Dragonfly), J2032+4127

Normalized weighted light curve (100 bins) in the 0.3-10 GeV range (blue) and unweighted light curve above 10 GeV (pink): Credit: D. Paneque (Fermi Symposium 2012)
Pulsar Wind Nebulae

- Relativistic particles injected by the central pulsar
- Ejecta of the supernova swept up
- Flow decelerated by the shock
- Particles are accelerated at the shock (Diffusive Shock Acceleration, Resonant cyclotron absorption, etc.) and radiate

Credits: J. Hinton

(Gaensler & Slane. 2006. ARA&A, 44, 17)
A growing population detected by the LAT

1- Young PWNe:
- Crab Nebula (Abdo et al., 2010, 708, 1254)

2- Middle aged PWNe:

3- PWNe candidates:
- HESS J1023-575 (Ackermann et al, 2011, 726, 35)  Likely
The Crab Nebula, the brightest VHE source...

The brightest VHE galactic «steady» source, observed by every Cherenkov experiment & Fermi (Abdo et al, 2010, 708, 1254):
- γ-ray emission below 500 MeV due to synchrotron emission
  → electrons accelerated up to ~1 PeV
- high energy component due to IC (mainly on synchrotron photons)
  → fit of the IC peak at ~60 GeV (using Fermi and IACT results)
  → magnetic field constraint in the 100 - 200 μG range

E. de Cea del Pozo, ICRC 2011

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... but no more a standard candle


- Average flux $\sim 6 \times 10^{-7}$ ph/cm$^2$/s above 100 MeV, with three flares as extremes of persistent variability

- Flux increase by $\sim 5$ during 2009 and 2010 flares, by $\sim 30$ during 2011 flare!

- Compact emission region $< 0.0004$ pc $\sim 0.04''$ (for $D<4$) $\rightarrow$ Emission from the inner nebula

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The puzzling Vela X PWN

- Associated with the Vela Pulsar (d = 290 pc)
- Located south of the pulsar

**Morphology:**
- Radio & HE gamma-rays: Halo (2° x 3°)
- X-rays & VHE: Cocoon (length < 1°)

**Multiwavelength spectrum:**


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*Multi-wavelength spectrum of Vela X*
...and even more puzzling!

Lower energy threshold (300 MeV, front events)
- Morphological analysis in different energy bands
  → unveils an energy-dependent morphology

- 300 MeV - 1 GeV (red):
  HE emission matches the radio halo (yellow contours)

- Above 1 GeV (green):
  correlates only with the « Western » wing of the radio emission

(As reported in the 1st Fermi paper)

Grondin et al., to be submitted
A PSR-like PWN candidate! MSH 11-62

1FGL J1112.1-6041 is spatially associated with MSH 11-62

- Radio observations reveal shell with bright nebula in center
  - no pulsar known, but surely a PWN
- X-ray studies show thermal shell with a central PWN:
  - pulsar candidate seen at the center of the PWN (offset from radio center)

- if the GeV emission is produced by the PWN, broadband modeling appears to provide additional support for presence of Maxwellian electron component

Fermi observations of MSH 11-62 are consistent with emission arising from an evolved PWN, but pulsar hypothesis cannot be ruled out
=> timing is extremely important

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Going further: Search for TeV PWNe in the GeV range

Second search for PWNe and PWNe candidates using Fermi-LAT data:
- Search in the off pulse
- Search at high energy around TeV sources

Why?
PWNe are the most populous class of Galactic sources in the TeV energy range
~1/3 of TeV Galactic sources are UNID → potential PWNe
→ TeV information on the position and extension could improve sensitivity.

What are we looking for?
- New GeV detections
- Study the morphology
- Constraints on the SED models

Which candidates?
- Select only Galactic sources (latitude of +/- 5°) which are not identified as SNRs
- Remove the Galactic center for reliability and Vela X

⇒ 58 sources to analyze above 10 GeV (good PSF, reduce Galactic bckg)
The Galactic Plane as seen by the LAT

Background subtracted counts map smoothed with a Gaussian of 0.27°
The Galactic Plane as seen by the LAT

Background subtracted counts map smoothed with a Gaussian of 0.27°
Another GeV PWN: K3

The complex of compact and extended radio/X-ray sources, called Kookaburra (Roberts et al. 1999), spans over one square degree along the Galactic plane.

It contains 2 PWNe detected at TeV: HESS J1420-607 and HESS J1418-609.

LAT GeV emission on HESS J1418 vanishes above 30 GeV; but still bright signal coming from HESS J1420: indicates a potential PWN detection by the LAT.

Detected also at E>100 GeV by Neronov and Semikoz (2012; arXiv1201.1660).

Background subtracted counts map smoothed with a Gaussian of 0.27°.

**HESS J1420-607 and the GeV-TeV connection**

Models point towards an association of the GeV emission with the TeV PWN HESS J1420-607.

At low energy (10-30 GeV) the SED of HESS J1420-607 might be contaminated. Excellent GeV-TeV connection.

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A new GeV PWN: HESS J1356-645

HESS J1356-645 is an extended source detected in the TeV energy range by H.E.S.S. during the Galactic Plane Survey.

Its high spin-down power of $3.1 \times 10^{36}$ erg s$^{-1}$ makes it a good PWN candidate.

Significant detection with Fermi and very hard spectrum matching the TeV flux (both detected in the off-pulse search and the TeV search)

=> point towards an association of the GeV and TeV sources

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PWNe in the GeV range: towards a real population

Already 6 PWNe clearly identified + several PWNe candidates

→ So far, Fermi detects PWNe powered by bright (energetic) and young Pulsars
→ Efficiency < 10% of the spin-down power of the powering pulsar is required to explain the gamma-ray luminosity above 100 MeV

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GeV observations: summary

- Already 117 Pulsars detected by Fermi-LAT: 77 young or middle aged PSR + 40 MSPs
  - Superb sensitivity has enabled phase-resolved spectroscopy and detailed light curve studies of many pulsars
- 1 New MSP detected by blind frequency searches: very good prospect for the future!
- 6 identified PWNe and a dozen of good candidates associated to TeV PWNe
  - 2 young PWNe: Crab and MSH 15-52
  - 4 middle aged PWNe: Vela X, HESS J1825, HESS J1356, HESS J1420
  - Some constraining ULs help to constrain the origin of the gamma-ray emission
- Potential sources of CR electrons ⇒ see talk by D. Grasso

⇒ A real population of Pulsars and PWNe is being detected by the LAT!
Stay tuned: the 2nd Pulsar Catalog and the PWNe search around TeV Galactic sources will be submitted very soon

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Growing and growing...

36-month all-sky image. Pass 7.6 Source class events

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Growing and growing...

+ 2PC Pulsars

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Growing and growing...

PWNe identified and candidates

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And many more to come soon!

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