Pulsar Emission above the Spectral Break:

A Stacked Approach

[withe some new results on Geminga From VERITAS]

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Fermi Symposium-2014
Nagoya, Japan
Question:

The VHE pulsar catalogue contains only one source \( \text{(the Crab pulsar)} \)

\[ \text{Is VHE}^\dagger \text{ emission above the break common in other pulsars?} \]

Where to look for the answer:

What do we see in the bright Fermi pulsars? \( \text{(where we have good statistics above 10 GeV)} \)

What do we see above 100 GeV in Geminga? \( \text{(the brightest Fermi pulsar in the North)} \)

Is there low-level emission from Fermi pulsars? \( \text{(which cannot be resolved in individual pulsars but can be detected from stacked analysis of an ensemble)} \)

\( ^\dagger \text{E} > 100 \text{ GeV} \)
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\(^{†}\) \(E > 100\) GeV
What we know from Fermi

Power-Law Plots from 2nd Fermi LAT catalog of gamma-ray pulsars doi:10.1088/0067-0049/208/2/17

- Crab Pulsar
- Geminga Pulsar
- Vela Pulsar
- PSRJ 2021+4026
What we know from Fermi

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Cut-off?
What we know from Fermi

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harder than exponential?
What we know from Fermi

- Crab Pulsar
- Geminga Pulsar
- Vela Pulsar
- PSR J2021+4026

Upper-limits

Energy (GeV)

$E^2 dN/dE$ (erg cm$^{-2}$ s$^{-1}$)
What we know from Fermi

Power-Law

Cut-off?

harder than exponential?

Break

Upper-limits
What we know from Fermi

Power-Law harder than exponential?

Cut-off?

Break

Upper-limits

What is going on here?
What we know from Fermi

Power-Law

Cut-off?

harder than exponential?

Break

Upper-limits

Power-law?
What we know from Fermi

- Power-Law
- Cut-off?
- New Component?
- Break
- harder than exponential?
- Upper-limits
What we know from Fermi

Power-Law

Cut-off?

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Break

Upper-limits
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NEW: VERITAS observation of Geminga

- **72 hours** of VERITAS observations
- **5.2 years** of Fermi data
- Fermi profiles fit above 5 GeV for P1 and 10 GeV for P2
- +/- 1 sigma width phase gates for phase resolved SEDs
- P1 [0.072 – 0.125]
- P2 [0.575 – 0.617]
- Background selected from [0.7 – 1.0]
- VERITAS cuts optimised *a priori*
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NEW: VERITAS observation of Geminga

- No significant emission seen by VERITAS above 100 GeV
- $H^2$-Test value of 1.8 which is equivalent to $0.7\sigma$.
- Event counts in P1 and P2 phase gates fully consistent with background counts
- VERITAS limits at the 0.3% Crab Nebula flux level above 135 GeV.
- Pure power-law extension of the Fermi SED above 10 GeV below the derived limits.
- Paper submitted to ApJ.
VERITAS limits at the 0.3% Crab Nebula flux level above 135 GeV.

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Aperture Photometry with Pulsars

Crab Pulsar

- Weekly files with 5.2 years of pass7 reprocessed data
- gtselect run in 16 logarithmically-spaced energy bins with an energy dependent ROI cut
- gtmktime run with 100 deg zenith cut
- EVENT tables merged and folded with timing solution from Kerr et al 2014
- Cross-correlation analysis with profile from 2nd PSR cat. to get “phase shift”
Crab Pulsar

Crab PSR profile from the 2nd LAT PSR cat.
Aperture Photometry with Pulsars

Crab Pulsar

\[ \alpha = \left( \frac{\text{PR}_\text{off}}{\text{PR}_\text{on}} \right) \]

2nd Pulsar Cat.
Aperture Photometry with Pulsars

Crab Pulsar

ON

Entries 379291
Mean 2.432
RMS 0.36

OFF

Entries 83516
Mean 2.325
RMS 0.2802

ON

OFF

Log10(Energy/MeV)

Log10(Energy/MeV)
Aperture Photometry with Pulsars

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Aperture Photometry with Pulsars

Crab Pulsar

- Entries: 164536
- Mean: 2.572
- RMS: 0.4021
Aperture Photometry with Pulsars

Crab Pulsar

Entries 164536
Mean 2.572
RMS 0.4021
Aperture Photometry with Pulsars

Crab Pulsar

Exposure [cm$^2$ s]

Entries 16
Mean 4.146
RMS 1.005

Log10(Energy/MeV)

100 MeV  316 MeV  1 GeV  3.16 GeV  10 GeV  31.6 GeV  100 GeV  316 GeV  1 TeV
Aperture Photometry with Pulsars

- `gtbin` run for each energy range with the whole duration as the bin width
- `gtexposure` run with `specin=-2` and `apcorr='yes'` and the corresponding energy dependent ROI.

Crab Pulsar

- Entries: 16
- Mean: 4.146
- RMS: 1.005

Exposure [cm² s]

Log10(Energy/MeV)

100 MeV 316 MeV 1 GeV 3.16 GeV 10 GeV 31.6 GeV 100 GeV 316 GeV 1 TeV
Aperture Photometry with Pulsars

Crab Pulsar

- SED created without
  - any likelihood fitting
  - any XML files
  - any model assumptions (almost)
Aperture Photometry with Pulsars

Crab Pulsar

Energy [MeV]

$E^2 dF/dE$ [erg s$^{-1}$ cm$^{-2}$]
Aperture Photometry with Pulsars

- Aperture photometry SEDs made with other pulsars.
- Spanning 3 decades in flux, aperture photometry SEDs look very similar to likelihood (2nd pulsar catalogue).
Aperture Photometry with Pulsars

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- Spanning 3 decades in flux, aperture photometry SEDs look very similar to likelihood (2nd pulsar catalogue).
- Agreement within ~10-20%
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Aperture Photometry with Pulsars

- Stack the On/Off regions of 112 pulsars from the 2nd LAT PSR Cat.
- Average of 4.5 years of data per pulsar (limited by availability of timing solution)
- Crab pulsar excluded
- On/Off phase gates listed in 2nd LAT PSR Cat.
Aperture Photometry with Pulsars

Excess

Log10(Energy/MeV)

100 MeV 316 MeV 1 GeV 3.16 GeV 10 GeV 31.6 GeV 100 GeV 316 GeV 1 TeV

Excess Counts

10^6 10^5 10^4 10^3 10^2 10 1

56.2 GeV 100 GeV 177 GeV

Log10(Energy/MeV)
Aperture Photometry with Pulsars

Significance

Log10(Energy/MeV)

100 MeV  316 MeV  1 GeV  3.16 GeV  10 GeV  31.6 GeV  100 GeV  316 GeV  1 TeV

56.2 GeV  100 GeV  177 GeV
Aperture Photometry with Pulsars

Average Flux = \left( \frac{\text{Total Excess}}{\text{Total Exposure}} \right)

Fermi/VERITAS Crab Fit

[Aliu et al 2011]
Limits on the emission from pulsars

74 “young” Pulsars

Average Young PSR Flux
If there is emission from these 74 pulsars between 56 and 100 GeV, the average level is below 20% of the Crab PSR emission:

- 74 (100%) emitting at 20% Crab PSR

or

- 14 (20%) emitting at 100% Crab PSR and 60 (80%) at zero Crab PSR

or

- 3 (4%) emitting at 500% the Crab PSR and 71 (96%) at zero Crab PSR
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  or
- 14 (20%) emitting at 100% Crab PSR and 60 (80%) at zero Crab PSR
  or
- 3 (4%) emitting at 500% the Crab PSR and 71 (96%) at zero Crab PSR
Limits on the emission from pulsars

5.2 years of Geminga
A dedicated analysis of Geminga (and likely other pulsars) with 5yrs of data can set a limit of ~35% Crab pulsar in the 56-100GeV range.
If there is emission from these 74 pulsars between 100 and 177 GeV, the average level is below 65% of the Crab PSR emission:

- 48 (65%) emitting at 100% Crab PSR and 27 (35%) at zero Crab PSR
  or
- 4 (5.4%) emitting at 1200% the Crab PSR and 70 (94.6%) at zero Crab PSR
38 MSPs

ON|OFF Counts

Excess

Significance

Average Flux
If there is emission from these 38 pulsars between 56 and 100 GeV, the average level is below 20% of the Crab PSR emission:

- 38 (100%) emitting at 20% Crab PSR
- 7 (20%) emitting at 100% Crab PSR and 31 (80%) at zero Crab PSR
- 2 (5%) emitting at 380% the Crab PSR and 36 (95%) at zero Crab PSR
74 “young” PSRs V 38 MSPs

74 “young” Pulsars

38 MSPs

Average Young PSR Flux

Average MSP Flux
Average spectral shapes look very similar.

Average flux from MSP is ~1.5 orders of magnitude lower.

Fit with broken power law.

Power-law index before the break is 1.61 – 1.65.

MSP break energy is ~1 GeV higher than YP.
Conclusion

- From Fermi we know:
  - There are 147+ gamma-ray pulsars.
  - They have power-laws with spectral breaks between 1-10 GeV.
  - The bright ones show harder than exponential cut-offs.
  - Above ~50 GeV the fluxes are so low that there are only upper-limits.

- The Geminga Pulsar has been observed by VERITAS for 72hrs.
  - VERITAS sees no emission above 100 GeV from Geminga.
  - Limits cannot rule out a power-law extension of the Fermi SED.

- Stacking!
  - An “aperture photometry” method has been shown to work well for pulsar SEDs.
  - A stacking analysis has been performed on 112 Fermi pulsars.
  - No significant signal seen above 50 GeV.
  - Limits on the average flux from young pulsars & MSPs between 56-100 GeV are 20% Crab PSR.
  - Average young pulsar and MSP SEDs very similar. MSP break is ~1 GeV higher.
  - Future directions – Pass8 + stacking via composite likelihood.