Gamma-ray Pulsars

with

the *Fermi* satellite

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Actually, AGILE scooped *Fermi* for this first post-EGRET pulsar:


For more AGILE results, see Marco Tavani’s talk, Friday.
Large Area Telescope
30 MeV to 300 GeV

The whole sky, 8 times per day

GBM
2nd instrument
Gamma-ray burst monitor
48 months of data
>1 GeV. 4.52M events. Pass 7v6 Source class events from August 4, 2008 through August 4, 2012.
LAT rocking angle <52° and zenith angle <100°.

Point sources in the plane are mostly pulsars.
(Off the plane, mostly blazars. Also MSPs, and globular clusters w. MSPs.)
2FGL
LAT 2nd Source Catalog

Red: id’d.
Blue: Assc’d.
Black: UnId. == Gold mine!

4-year version, within the LAT team.
(submitted to ApJ Suppl 2 weeks ago.)

The catalog contents are online at
http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2nd_PSR_catalog/

Described in loving detail in Appendix B.

46 pulsars in “1PC” (6 months data),
Gamma-ray deathline seems near spin-down power $\dot{E} = 4I\pi^2 \dot{P}/P^3$ of a few $1 \times 10^{33}$ erg/s.

In globular clusters.

Double pulsar, J0737.

Uncertainties in Shklovskii correction.

$117(+8)$ gamma-ray pulsars in 2PC. 20 more to be published $\Rightarrow 145$ total.
Radio-quiet pulsars have no DM (Dispersion Measure): assign limit at MW edge (using NE2001).

Not an MSP in the Galactic center.

MSP in a globular cluster above the center.

``Anatomically correct” Milky Way.

Radio selected LAT pulsar
Gamma selected LAT pulsar
LAT millisecond pulsar

2PC Fig 4.
Three ways to discover gamma-ray pulsars

1. “PSUE” = “Pulsar Search Using Ephemerides”:
   • Phase-fold gamma-rays using rotation parameters of a known pulsar.
   • Weights from spectrum⊗point-spread-function eliminate ~few trials over ROI & energy cuts. But… spectra tricky for faint pulsars.
   • Except Geminga, all Fermi PSUE’s from radio, not X-rays.

2. Blind period search in gamma-rays at target** positions :
   • 41 young PSRs. One MSP, J1311-3430.
   • Only 4 radio detections.

3. Deep radio search at UnId gamma positions :
   • 46 MSPs, off the plane. ~Few young, and/or accidental coincidences.
   • Can take a year before PSUE allows pulsed gamma detection.

** Targets: early in mission, e.g. X-ray CCO’s. Later, UnId gamma sources. Now also deep X-ray and optical companion searches.

See Pablo Saz Parkinson’s talk.
Campaign to time 224 high Edot pulsars. (best gamma-ray candidates, but unstable spin-down rate.)

We obtained another 700 ephemerides.
Above: 3-year point-source sensitivity, assuming pulsar-like spectra.

Right: Ditto, averaged over longitude, showing 10%, 90% percentiles. “PSUE” are the radio, X-ray point. Else, $\gamma$ blind search.

- PSUE is easiest*, and picks up fainter pulsars than the catalog point source search.
- BUT suffers the same selection biases as ‘historical’ radio surveys.
- Gamma-triggered pulsar detections unveil complementary neutron star populations.

* Because your radio and Xray friends did the hard part!
Blazars (AGNs) are variable, with power-law spectra.

Pulsars are steady, with cut-off spectra.  
(New – learning to ignore cut-offs.)

LAT sources are well-localized.

\textit{Pablo's talk}: target selection, and gamma blind searches.
MSPs from pre-*Fermi* radio surveys are slower than the *Fermi*-induced discoveries.


‘PSC’ = *Fermi* Pulsar Search Consortium = radio astronomers coordinating deep searches of *Fermi* unidentified sources.
Many Fermi MSPs are Black Widows and Redbacks.
Rare before Fermi.

Explore the recycling process.
See Mallory Roberts talk, today.
• The MSPs are faint:
  low $\dot{E}$ $\Rightarrow$ low $L_\gamma$ $\Rightarrow$ nearby $\Rightarrow$ big latitude spread.

• The \textit{Fermi} “treasure map” has allowed deeper, repeated (scintillation! eclipsing!) radio searches than radio surveys.
• Some new radio MSPs ‘good timers’ suitable for gravity wave searches.
• Four gamma blind-search pulsars detected in radio.
• Define “quiet” as $S_{1400} < 30 \mu$Jy.
• *Fermi* allows probe of radio parameter space.

Diagonal : $100 \mu$Jy-kpc$^2$ pseudo-luminosity.
Radio pulsars have a limited range of magnetic ($\alpha$) and overall ($\zeta$) inclinations: the radio beam must sweep the Earth.

LAT shows, $\gamma$-ray beams are mostly *wide*: large number of young, radio-quiet pulsars.

MSPs have a smaller light-cylinder. The magnetic field lines are cut close in, making broader radio beams.

No radio-quiet MSPs yet. Expect few or none.

*Not* in 2PC – compilation of ($\alpha, \zeta$) estimates, from radio polarization (e.g. RVM), or pulsar wind nebulae inclinations (e.g. X-ray images).

(S. Johnston; M. Kerr, R. Shannon working on it…)

Many individual gamma pulsar papers provide those analyses. Useful for modeling *(we hope)*.
2PC: characterizing gamma-ray pulsars

• Gamma pulse profiles in different energy bands. Profile fit for >0.1 GeV. Radio when available; background levels; off-pulse.

• Spectral fits for all but the very faintest. Power law with pure exponential cutoff works well, generally. Provide alternatives when called for.

• “The pulsars not seen” – tabulate undetected good candidates.

• X-ray and optical compilations for the 117 γ-pulsars.

• All of the above in the online FITS, image, and ascii files.
Profile example: PSR J2240+5832
(see also Theureau et al. 2011, A&A, 525, A94)

- Black – weighted gamma-ray profiles.
- Blue – fit
- Red – phase-aligned radio profile.
- Gray – ‘off-peak’ phase range
- Horizontal dash – local gamma-ray b’grd

- $d = \delta$ = ‘radio lag’
- $D = \Delta$ = ‘peak separation’
- H-test pulse significance

Online files have these in .png, .pdf, .FITS, and ascii.

Online files also contain the leading and trailing half-widths of the gamma peak(s).
Gamma-ray pulse profile shapes

LAT Second Pulsar Catalog, Abdo et al., in prep.
For radio-loud gamma pulsars: closer peaks means bigger offset from radio pulse.

A geometrical effect, but also depends on gap size (see Christo’s talk)
Large gamma-ray sample: test models for a broad range of magnetic (\( \alpha \)) and overall (\( \zeta \)) inclinations.

(this is an XMM conference – the caricature of a thermal X-ray pulse profile is the aberrated sinusoïd of a hot polar cap: *strikingly different.*)

\[ \zeta \text{ vs phase } \phi. \]

Fan-like beam. Here, “slot gap” model.

Cut across some line-of-sight \( \zeta \).
Compare data with simulated “atlases” of predicted gamma-ray pulse profiles, for different models, magnetic inclinations $\alpha$, and inclinations $\zeta$ to the line-of-sight.


Gap size scales $\propto 1/\sqrt{\dot{E}}$.

Match observed to predicted profiles.

See also e.g.
Venter et al (2012)
and
Pétri MNRAS (2011)
and
Pierbattista, Grenier, Harding, Gonthier, arXiv:1103.2682
and
Bai & Spitkovsky 2009
\[
\frac{dN}{dE} = N_0 E^{-\Gamma} \exp \left( -\frac{E}{E_0} \right) \text{ cm}^{-2} \text{s}^{-1} \text{GeV}^{-1}
\]

b=1 \implies \text{high altitude curvature radiation.}

(strong magnetic fields near surface "absorb" gammas.)

This said – as the mission progresses, we study fainter & fainter sources, and spectral details become less discriminating.

**Pulsar spectral ‘signature’**.

(Most sources, e.g. blazars, have power law spectra with little or no curvature.)

Future: a) subtler candidate selections b) search ‘em all!
The brighter the pulsar, the more phase bins with enough statistics for a full spectral analysis.

*Not* done in 2PC. See individual papers*

Phase-averaged spectra often show sub-exponential cutoffs ($b<1$).

Generally an *artifact* of the sum of varying spectral shapes.

*e.g. Megan DeCesar (this) and Nicolas Renault doctoral theses.*
Spectral evolution.
See Jérôme Pétri, C. Venter talks for emission modeling.
Gamma luminosity: a key observable, but with difficulties:

- Distance $d$ dominates luminosity $L_\gamma$ uncertainties.
- The model “beam factor” $f_\Omega$ depends on the inclinations $\alpha, \zeta$ of the magnetic and rotation axes.

\[
L_\gamma = 4\pi d^2 f_\Omega G_{100}.
\]

\[
f_\Omega(\alpha, \zeta_E) = \frac{\int F_\gamma(\alpha; \zeta, \phi) \sin(\zeta) d\zeta d\phi}{2 \int F_\gamma(\alpha; \zeta_E, \phi) d\phi}
\]

Radio polarization and X-ray nebula images help constrain $\alpha, \zeta$ …

$G_{100}$: integral energy flux $>$100 MeV
Gamma-ray luminosity versus spindown power

For Crab, include Xray flux.

Uncertainties in Shklovskii correction.

\[ L_\gamma = 4\pi d^2 f_\Omega G_{100} \]

- \( d \): Pulsar distance
- \( f_\Omega \): ‘beam fraction’ (set to 1)
- \( G_{100} \): integral energy flux >100 MeV

2PC Fig 9.
X-ray spectral compilation

and the explosive power of positive feedback

from 2PC  Table 16.  X-ray spectral parameters of LAT-detected MSPs
(an extension of M. Marelli et al’s work.)

<table>
<thead>
<tr>
<th>PSR</th>
<th>Inst</th>
<th>$N_H$</th>
<th>$F_X^{n_{\gamma}}$</th>
<th>Sp. Type, pulsed</th>
<th>$G_{100}/F_X^{n_{\gamma}}$</th>
<th>$F_X^{pwn}$</th>
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<tr>
<td>J0023+0923</td>
<td>C</td>
<td>5$^c$</td>
<td>0.21$^{+0.20}_{-0.17}$</td>
<td>Pow</td>
<td>381$^{+374}_{-321}$</td>
<td>…</td>
</tr>
<tr>
<td>J0030+0451</td>
<td>X</td>
<td>6.4$^{+3.4}_{-2.4}$</td>
<td>2.55$^{+0.29}_{-0.06}$</td>
<td>BB+Pow, P</td>
<td>241$^{+29}_{-8}$</td>
<td>N</td>
</tr>
<tr>
<td>J0034−0534</td>
<td>X</td>
<td>&lt;56.3</td>
<td>&lt;0.06</td>
<td>BB</td>
<td>&gt;2800</td>
<td>N</td>
</tr>
<tr>
<td>J0161−0422</td>
<td>S</td>
<td>1$^{c}_{-2.7b}$</td>
<td>2.31$^{+0.34}_{-0.34}$</td>
<td>--</td>
<td>&gt;45.3$^{+3}_{-280}$</td>
<td>--</td>
</tr>
<tr>
<td>J2214+3000</td>
<td>C</td>
<td>&lt;21.3</td>
<td>0.74$^{+0.03}_{-0.27}$</td>
<td>Pow</td>
<td>441$^{+34}_{-3}$</td>
<td>…</td>
</tr>
<tr>
<td>J0915+5125</td>
<td>C</td>
<td>100</td>
<td>0.77$^{+0.27}_{-0.27}$</td>
<td>P</td>
<td>150$^{+17}_{-17}$</td>
<td>…</td>
</tr>
</tbody>
</table>

XMM pulsations for a new LAT MSP, Mike Wolff et al (NRL), in 2012 Fermi Symposium.

Gamma ⇔ radio ⇔ X-ray ⇔ theory feeding frenzy.

The X-ray pulse profile applying the Nancay radio ephemeris in the 0.32 – 1.51 keV energy range. The detection significance with the H-test (da Li Long Buchheim 2010, A&A, 517, L1) is 7.95, and pulsed.
The future: **MORE** gamma-ray pulsars

“The dark corners of parameter space” – dream of seeing not just the *bright* ones (nearby; high $\dot{E}$, perhaps due to strong $B_S$; favorable $\alpha, \zeta$; low background regions) but also a sampling that allows model tests for atypical parameters.

*Multiple approaches in progress:*

- Search for gamma-quiet pulsars: F. Acero talk, Friday.  

- Point-source search seeding with pulsar-like spectra (Toby Burnett).

- ‘Pass 8’ – better acceptance at low energies good for pulsars.  
  *‘P7REP’ (= ‘reprocessed Pass 7’) already giving performance gains.*

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**Pass 8: Toward the Full Realization of the Fermi-LAT Scientific Potential**

The future: **fainter** gamma-ray pulsars

From Xian Hou’s poster –

- J1705, lowest $\dot{E}$ young radio pulsar.
  *One of 3 young $\gamma$ pulsars with radio interpulse.*
- J1640, J1732, low $\dot{E}$ MSPs
- J1055, far, in plane.
- J1913, hi b’grd

![Preliminary graph showing pulsar data with various symbols and lines indicating different types of pulsars and their properties.](image)
Thank you!

All LAT team publications at
https://www-glast.stanford.edu/cgi-bin/pubpub

David A. Smith,

para muchas personas.
Curvature Radiation

Matches most of what we see
(as does $b=1$)

even if inverse compton scattering, other, may also occur in some cases (e.g. pulsed Crab TeV)

$$\gamma_{\text{lim}} = \left( \frac{eE_{\parallel}}{5.6 \times 10^{-3} mc} \right)^{1/4} \rho^{1/2}$$

$$\approx 5.1 \times 10^7 \left( \frac{X_e B_{12}}{P_{-1}} \right)^{1/4} \rho^{1/2}$$

Radiation losses limit acceleration by $E_{\parallel}$.
(electric field component parallel to the B-lines.)

Radius of curvature $\rho \approx R_{\text{LC}}$

$X_e$ is the fraction of the open-field line region where acceleration works (‘gap size’).

Romani ApJ 1996 : $X_e \propto \sqrt{\dot{E}}$

**Paradox:**
High luminosity means wide gaps. Narrow peaks means narrow gaps.
Most power in gammas (for known $\gamma$ psr's) (i.e. high $E_\dot{}$ pulsars).

~2200 known radio pulsars (millions must exist)

( "millions": ~1 supernova/century x ~10 Gyr = $10^8$. They live mega-years.)

~ 50 in X-rays, 6 in optical, and, before Fermi, $\leq$10 in $\gamma$-rays.

Few percent of $E_\dot{}$ in gammas. >80% in the wind!


Atypical 3rd peak ("shoulder") drifts with phase. Two main peaks are typical. (here, 3 years of data.)

By Thierry Reposeur, Bordeaux.
How pulsars are interesting and/or useful:

**Interesting in their own right. But also:**

- Unresolved (distant) pulsars contribute to diffuse gamma emission. ~10%, increasing at higher energies.
  - Diffuse model tests [(cosmic rays) ⊗ (dust, gas)] throughout Milky Way.
  - Diffuse model allows deep, uniform (“complete”) population samples.
  - Especially for faint things like, perhaps, Dark Matter signatures.

- On the origin of cosmic rays
  - Pulsar Wind Nebulae (PWN) can be confused with supernova remnants (SNRs), probable proton etc accelerators. Identifying PSRs helps.
  - Towards complete PWN models: pulsar wind and B field as inputs.
  - PWNe dominate TeV sky. But there are UnId’d TeV sources too.
  - Nearby pulsars contribute to the local e+ e- flux,
    - a foreground to *other* Dark Matter signatures.

- “Endpoint of stellar evolution” – pulsar census to cross-check massive star tallies & supernova rates.

- To get MSP population right, need to understand the young pulsars. GWs!
• Chandra X-ray images of the PWN can give the angle $\zeta$ of the pulsar rotation axis relative to the Earth line-of-sight.

• *Fermi* LAT sees pulsations for 7 of these 9.
  

Image Model

Ng & Romani et al. 2008