Gamma-ray Pulsars
and search for gamma-quiet ones
with *Fermi*

David A. Smith, for the *Fermi* LAT collaboration
Centre d’Études Nucléaires de Bordeaux-Gradignan
(CENBG / IN2P3 / CNRS)
smith@cenbg.in2p3.fr

Bordeaux, 16 Novembre 2010
Large Area Telescope
30 MeV to 300 GeV

The whole sky, 8 times per day:
• Known sources, as well as unexpected sources.
• Better localization than previous instruments.
# Summary of Fermi LAT science publications

15 November 2010

## Category I and II papers in refereed journals

<table>
<thead>
<tr>
<th>Journal</th>
<th>Published</th>
<th>In press</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astronomy and Astrophysics</td>
<td>2+1=3</td>
<td>2+1=3</td>
<td>6</td>
</tr>
<tr>
<td>Astroparticle Physics</td>
<td>1+2=3</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Astrophysical Journal</td>
<td>46+5=51</td>
<td>3+1=4</td>
<td>55</td>
</tr>
<tr>
<td>Astrophysical Journal Letters</td>
<td>16+3=19</td>
<td>1+0=1</td>
<td>20</td>
</tr>
<tr>
<td>Astrophysical Journal Supplement</td>
<td>3+0=3</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Journal of Cosmology and Astroparticle Physics</td>
<td>2+2=4</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>Nature</td>
<td>2+0=2</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Physical Review D</td>
<td>1+0=1</td>
<td>2+0=2</td>
<td>3</td>
</tr>
<tr>
<td>Physical Review Letters</td>
<td>4+0=4</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>Science</td>
<td>9+0=9</td>
<td>-</td>
<td>9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>86+13=99</td>
<td>8+2=10</td>
<td>109</td>
</tr>
</tbody>
</table>

Papers submitted to journals: 15
Near submission: 5
Published category III papers: 29

arXiv: 1002.2280

Currently: 24 month catalog under study within the team. Cut-off spectra for pulsars. Improved diffuse model. Improved analysis < 200 MeV. 2nd year catalog after Christmas.
74 + 14 LAT Pulsars and growing...

30 Young Radio-selected
26 Young γ-selected
6 γ-sel MSP γ/R pulse
13 MSP Radio-selected
14 γ-sel MSP R pulse
"First Fermi LAT Catalog of gamma-ray pulsars",


Plot by Denis Dumora, Bordeaux
About the LAT pulsars

• Generally (but not always), two peaks separated by ½ rotations.

• Generally (but not always), gamma peak offset from radio.

• Exponential cut-offs at ~1 to ~3 GeV.

• Favors outer magnetospheric emission.

• **MSPs resemble young pulsars.**  *Not so true anymore.*

• Now several MSPs where the gamma and radio peaks are aligned.
two examples

Pulsed Gamma-rays from the MSP J0030+0451 with Fermi

Pulsed gamma-rays from PSR J2021+3651 with the Fermi LAT
Fig. 4.— Phase difference $\Delta$ between the gamma-ray peaks, versus the phase lag $\delta$ between the main radio peak and the nearest gamma-ray peak. Pulsars without a radio detection are plotted with $\delta = 0$. With present light curves we cannot generally measure $\Delta < 0.15$; objects classified as single-peaked are plotted with $\Delta=0$. Two such objects, both MSPs, are off the plot at $\delta > 0.8$. 

*1st Fermi $\gamma$-ray pulsar catalog*,
Campaign to time 224 high Edot "Egret-like" pulsars. Nançay, Jodrell Bank, Parkes "gave" us another 500 ephemerides. Westerbrok, Urumqi, GMRT-India also involved. If you need rotation ephemerides, contact us.

Excellent working relation with the radio and X-ray pulsar experts.

Pulsar Timing for the Fermi Gamma-ray Space Telescope

D. A. Smith\textsuperscript{1,2}, L. Guillemot\textsuperscript{1,2}, F. Camilo\textsuperscript{1}, I. Cognard\textsuperscript{3,5}, D. Dumora\textsuperscript{1,2}, C. Espinoza\textsuperscript{6}, P. C. C. Freire\textsuperscript{7}, E. V. Gotthelf\textsuperscript{3}, A. K. Harding\textsuperscript{8}, G. J. Johnston\textsuperscript{9}, N. Manchester\textsuperscript{9}, F. E. Matheson\textsuperscript{9}, B. W. Stappers\textsuperscript{9}

1 Université de Bordeaux
2 CNRS/IN2P3, Centre d’Astrophysique, Bordeaux
3 Columbia Astrophysics Lab
4 Laboratoire de Physique de l’Espace, Marseille
5 Station de radiotélescope, Saclay
6 University of Maryland
7 Arecibo Observatory
8 NASA Goddard Space Flight Center
9 Australia Telescope
10 McGill University
11 West Virginia University
12 National Radio Astronomy Observatory
13 Eureka Scientific
14 Department of Physics
15 Department of Astronomy
16 National Aeronautics and Space Administration

We describe a campaign with the Fermi Gamma-ray Space Telescope (formerly the GLAST) for searching for new high mass X-ray binaries and supernova remnants. The Fermi telescope is especially well suited to driving pulsar wind nebulae and supernova remnants with high energies, which makes detection of high angular resolution measurements possible. To search for new objects, a year or more is needed to complete a campaign. Attention has been paid to the analysis of a new pulsar PSR B1937+21 recorded in the microsecond level.

Key words: pulsars: general – Gamma-rays: observations – Ephemerides
\[ \frac{dN}{dE} = N_0 E^{-\Gamma} \exp \left( -\frac{E}{E_0} \right)^\beta \, \text{cm}^{-2} \text{s}^{-1} \text{GeV}^{-1} \]

LAT spectra for PSR J2021+3651

Fig. 7.— Value of the exponential cutoff $E_{\text{cutoff}}$ versus the magnetic field at the light cylinder, $B_{\text{LC}}$.

Fig. 8.— Photon index $\Gamma$ versus the rotational energy loss rate, $\dot{E}$. For $\Gamma$, the statistical uncertain-
Fig. 2. — Geminga light curve above 0.1 GeV using an energy-dependent ROI, shown over two pulse periods. The count rate is shown in variable-width bins, each one containing 400 counts bin$^{-1}$ and normalized to 100. Insets show the phase interval centered on the two peaks and on the “off pulse” region ($\phi = 0.1-0.9$), binned to 0.00125 in phase. The dashed line represents the contribution of the diffuse background estimated by selecting photons in this “off pulse” interval in an annulus around the source.

\[ P0 = 237 \text{ ms} \rightarrow 300 \text{ } \mu\text{s/bin} \]

(we see a structure smaller than 10 $\mu$s for one MSP)

Geminga pulsar with \textit{Fermi} LAT


Fig. 6. — Phase evolution of the spectral index (top) and energy cutoff (bottom) above 0.1 GeV as the function of the pulse phase, divided in phase bins each containing 2000 photons. Vertical bars indicate the combined statistical and systematic uncertainties. For each phase interval (defined in Table 2) a power law with exponential cutoff has been assumed. The shaded histogram represents the \textit{Fermi}-LAT light curve above 0.1 GeV in variable-width phase bin of 2000 photons/bin.
Deep searches for radio counterparts to pulsars discovered in gamma-ray blind period searches.

Precise Gamma-Ray Timing and Radio Observations of 17 Fermi Gamma-Ray Pulsars

Timing residuals of Fermi rotation ephemerides are of order of milliseconds.


Blind search pulsar #25 found last week.
Gamma-ray luminosity versus spindown power

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

5 gamma MSPs using Nançay -- 3 new!


L. Guillemot, Pulsar Conference 2010, 14/10/10
\[ f_\Omega(\alpha, \zeta_E) = \frac{\int F_\gamma(\alpha; \zeta, \phi) \sin(\zeta) d\zeta d\phi}{2 \int F_\gamma(\alpha; \zeta_E, \phi) d\phi} \]

\( f_\Omega \): total flux / flux beamed along one line of sight

- Fan-like gamma beam from "outer" or "slot" gap?
- Radio vs gamma pulse profiles  
  \( \Rightarrow \) Powerful model discriminant

- Below left: \( \zeta \) vs phase \( \phi \) for a "slot gap" model.
- Below right: Cut across some line-of-sight \( \zeta \).
Search for gamma-quiet pulsars

**what are the black dots at high $E_{\text{dot}}$?**

Plot by Denis Dumora, Bordeaux
Search for gamma-quiet pulsars

Two purposes:

1) Double-checking our gamma pulsar searches –
   • "Leave no stone unturned"
   • Timing ephemerides okay?
   • Closer look at distances, backgrounds of "interesting" pulsars.

2) Additional test of emission models!
   • Gamma quiet pulsars should occupy a little piece of $\alpha,\zeta$ space.
   • Check the angles (e.g. rotating vector model using radio polarization)
   • Check the numbers of gamma-loud vs gamma-quiet pulsars.

The "2nd Fermi Catalog of $\gamma$-ray pulsars" (Spring 2011?) will include upper limits for pulsars with large expected signal-to-noise.
   • Signal: $\sqrt{E/d^2}$
   • Noise: all other gamma sources (diffuse + neighbors)

Comparisons with model syntheses in progress.

| Rank | PSRJ       | Edot (erg/s) | Dist1 (kpc) | |b| (deg) |
|------|-----------|--------------|-------------|-------|
| 14   | J1740+1000 | 2.3E35       | 1.2         | 20.3  |
| 16   | J1357-6429 | 3.1E36       | 2.5         | -2.5  |
| 19   | J1524-5625 | 3.2E36       | 2.8         | 0.35  |
| 23   | J0940-5428 | 1.9E36       | 2.9         | -1.3  |
| 24   | J1930+1852 | 1.2E37       | 5.0         | 0.27  |
| 25   | J1302-6350 | 8.2E35       | 2.8         | -0.99 |
| 29   | J1846-0258 | 8.1E36       | 5.1         | -0.24 |
| 31   | J1826-1334 | 2.8E36       | 3.9         | -0.69 |
| 32   | J1809-1917 | 1.8E36       | 3.5         | 0.08  |
| 34   | J1811-1925 | 6.4E36       | 5.0         | -0.35 |
| 36   | J1803-2137 | 2.2E36       | 3.8         | 0.15  |
| 38   | J0117+5914 | 2.2E35       | 2.2         | -3.5  |
| 43   | J1617-5055 | 1.6E37       | 6.8         | -0.28 |
| 47   | J1913+1011 | 2.9E36       | 4.8         | -0.17 |
| 49   | J1739-3023 | 3.0E35       | 2.9         | 0.34  |
| 50   | J1831-0952 | 1.1E36       | 4.0         | -0.13 |

- Two pulsars with $\dot{E} > 1E38$ erg/s, unseen in gamma rays. They’re in the LMC! Just too far…
  

- Here: $1E35 < \dot{E} < 1E38$ erg/s, ranked by $\sqrt{\dot{E}/d^2}$

- J1740 wasn’t getting timed!

- J1617 very difficult to time – Parkes gave up. J1357 recovering from a big glitch.

- A few showing evidence for signals, at the 3 to 4 $\sigma$ level.

- Others may be good "gamma quiet" candidates. Constrain $\alpha, \zeta$ from radio polarization, calculate $f_\Omega$, and study gamma-ray upper limit.

Aitoff projection of LAT 5$\sigma$ sensitivity (log photon flux, ph /cm$^2$/s) for 6 months of sky-survey, for pulsar spectra with typical differential photon indices and exponential cutoff energies. (Figure 9 from "1st Psr catalog".)
Fig. 1. Phase-aligned γ-ray and radio light curves for PSR J0248+6021 obtained with the Fermi Large Area Telescope and the Nançay Radio Telescope. The bottom panels show the radio profiles at three frequencies.

Fig. 3. Expanded view of the radio polarization position angle sweep near the peak in radio intensity. The red points show the data used in the RVM fit. The black points failed the selection cuts described in the


Fig. 7. Pulsar geometry and emission modeling for PSR J0248+6021. Green contours show the rotating vector model fit to the radio polarization
Two important angles used to describe the emission geometry of pulsars are the angle $\alpha$ between the magnetic axis and the rotation axis and the angle $\zeta$ between the line of sight and the rotation axis. A related angle is the impact parameter $\beta = \zeta - \alpha$, which is the angle between the line of sight and the magnetic axis at its closest approach. These angles can be inferred by applying the rotating vector model (RVM; Radhakrishnan & Cooke 1969) to the position angle (P.A.) of the linear polarization observed in the radio band. This model predicts the P.A. of the linear polarization $\psi$ to depend on the pulse phase $\phi$ as

$$\tan(\psi - \psi_0) = \frac{\sin \alpha \sin(\phi - \phi_0)}{\sin \zeta \cos \alpha - \cos \zeta \sin \alpha \cos(\phi - \phi_0)},$$  \hspace{1cm} (4)$$

where $\psi_0$ and $\phi_0$ are the P.A. and pulse phase corresponding to the intersection of the line of sight with the fiducial plane (the plane containing the rotation and magnetic axis) if the emission height $h_{em}$ is small compared to the light cylinder distance. In this model, the P.A.-swing is an S-shaped curve and its inflection point occurs at $\phi_0$. 
At this point in the talk I showed the RVM explanation by Simon Johnston and Aris Karastergiou from the Barcelona pulsar conference in April 2010.

Conclusion

- *Fermi* LAT seeing a variety of pulsars in a variety of environments.
- Pulsars are the dominant gamma-ray foreground.
- High quality *Fermi* LAT and radio measurements constraining models.
Back-up slides

See publications at http://www-glast.stanford.edu/
About those distances...

**PSR J0248+6021:**
(l,b) = 137, 0.7
DM = 370 pc/cm³
NE2001: > 43.5 kpc

We argue for $2^{+2.4}_{-0.1}$ kpc
(said 2 to 9 in catalog)

**PSR J2240+5832:**
(l,b) = 107, -0.1
DM = 263.5 pc/cm³
NE2001: $10.3^{+∞}_{-3.3}$ kpc

We argue for $7.7^{±0.7}$ kpc

*Also APOD 2008 July 11*
Trois façons d'estimer les angles:

1. L'orientation $\zeta$ peut venir d'images du PWN en rayons X.

2. Comparaison des courbes de lumière gamma avec les modèles ("Atlas").

3. $\alpha, \beta$ peuvent venir de mesures de la polarisation radio et, par exemple, le RVM = Rotating Vector Model
‘Atlas’: reading off properties

- Note that X-ray PWNe can constrain $\zeta$

- Radio polarization sweep most sensitive to $\beta = \zeta - \alpha$.

This slide – Roger Romani.

*An Atlas for Interpreting Gamma-Ray Pulsars*
Fig. 3.— The $\chi^2$ map of the RVM fit of J0631+1036 (in gray scale, a darker color indicates a lower $\chi^2$). The lowest reduced $\chi^2$ is 1.45 and the solid contours correspond to reduced $\chi^2$ values that are two, three and four times larger. The half opening angles $\rho$ of the radio beam derived from the observed pulse width are overplotted (dotted contours).

Fig. 2.— The pulse profile at 1398 MHz observed at Nançay (black) of PSR J0631+1036, as well as the degree of linear polarization (dashed) and circular polarization (dotted). The bottom panel shows the PA of the linear polarization (if detected above 3$\sigma$) and an RVM fit.
The new MSPs have different selection biases. "Treasure map". Well-distributed on the sky.