Linking the soft $\gamma$-ray pulsar population with the Fermi LAT pulsar population: completing the high-energy picture

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Outline of presentation

- Pre-Fermi status (CGRO); Fermi LAT (>100 MeV) pulsar population
- Observational status of pulsar emission in the hard X-ray / soft γ-ray window (> 20 keV)
  - Increase of sample: How?
  - Work horses
- Current secure member list
- Update PSR B1509-58 & Vela
  - Zoom-in on some recent 'new' members AX J1838.0-0655, PSR J2229+6114 and IGR J18490-0000
- Population comparisons
- Summary & conclusions
Heritage
CGRO: 5 April 1991 – 4 June 2000
(20 keV – 30 GeV)

1) Classical $\gamma$-ray pulsars
   (SAS-2, COS-B)
   PSR B0531+21 (Crab)
   PSR B0833-45 (Vela)

2) Newly discovered high-energy $\gamma$-ray pulsars
   PSR B1706-44
   PSR B1055-52
   PSR B1951+32
   Geminga
   PSR J0218+4232, msp!
   PSR B0656+14
   PSR B1046-58

3) Newly discovered soft $\gamma$-ray pulsars
   PSR B1509-58
   PSR B0540-69 (RXTE HEXTE)
   (de Plaa, Kuiper, Hermsen 2003)

Only 4 pulsars detected in hard X-ray regime (> 20 keV)....
Spectral Energy Distributions

- Young pulsars, e.g. Crab, PSR 1509-58 reach maximum luminosity below 100 MeV

- Middle-aged Vela and older pulsars reach max. luminosity at GeV energies

- High-energy spectra of young pulsars are different from spectra of older $\gamma$-ray pulsars:
  
  $L_X/L_\gamma$ larger for young pulsars!
High-energy γ-ray (>100 MeV) pulsar population
Fermi LAT findings

Radio-loud: 42
Radio quiet: 35
Ms pulsars: 40 (recycled)
Young pulsars: 77 (non-recycled)

Simple exponential cutoff PL model ➔ Outer-magnetospheric emission

Maximum luminosity at GeV energies!

Abdo et al. 2013; ApJS 208, 17
With presently available sensitivities long exposures are required, sometimes summing (archival) data collected over years from:

<table>
<thead>
<tr>
<th></th>
<th>Instrument</th>
<th>Energy Range</th>
<th>Imaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>a)</td>
<td>RXTE PCA</td>
<td>(2 - 60 keV)</td>
<td>non-imaging</td>
</tr>
<tr>
<td>b)</td>
<td>RXTE HEXTE</td>
<td>(15-250 keV)</td>
<td>non-imaging</td>
</tr>
<tr>
<td>c)</td>
<td>INTEGRAL IBIS ISGRI</td>
<td>(15-300 keV)</td>
<td>imaging</td>
</tr>
<tr>
<td>d)</td>
<td>NuSTAR</td>
<td>(3 - 80 keV)</td>
<td>imaging</td>
</tr>
<tr>
<td>[e]</td>
<td>Suzaku HXD PIN</td>
<td>(12 - 60 keV)</td>
<td>non-imaging</td>
</tr>
<tr>
<td>f)</td>
<td>Swift BAT</td>
<td>(15-150 keV)</td>
<td>imaging</td>
</tr>
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</table>

Good imaging is required to avoid source confusion, particularly in Galactic Plane regions, and to disentangle pulsed and DC (PWN) emission.
Fleet of high-energy observatories


INTEGRAL 2002+  SWIFT 2004+  Fermi 2008+

Ground based TeV telescopes: HESS, MAGIC, Veritas, MILAGRO etc.
Soft γ-ray pulsar population (> 20 keV): 16 members

<table>
<thead>
<tr>
<th>name</th>
<th>period (ms)</th>
<th>age (kyr)</th>
<th>$10^9 \log(L_{ad})$</th>
<th>radio</th>
<th>pulse shape</th>
<th>photon index</th>
<th>Fermi LAT</th>
<th>TeV PWN</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSR B0531+21 (Crab)</td>
<td>33.5</td>
<td>1.23</td>
<td>38.66</td>
<td>bright</td>
<td>two pulses</td>
<td>curved</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>PSR B0540-69 (N158A in LMC)</td>
<td>50.5</td>
<td>1.7</td>
<td>38.18</td>
<td>very dim</td>
<td>structured broad</td>
<td>curved</td>
<td>no</td>
<td>...</td>
</tr>
<tr>
<td>PSR B0833-45 (Vela)</td>
<td>89</td>
<td>11</td>
<td>36.84</td>
<td>bright</td>
<td>multiple sharp</td>
<td>1.1</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>PSR B1509-58 (MSH 15-52)</td>
<td>150</td>
<td>1.6</td>
<td>37.26</td>
<td>bright</td>
<td>single broad</td>
<td>curved</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>PSR J1846-0258 (Kes 75)</td>
<td>324</td>
<td>0.72</td>
<td>36.91</td>
<td>quiet</td>
<td>single, broad</td>
<td>1.20(1)</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>PSR J1811-1925 (G11.2-0.3)</td>
<td>65.0</td>
<td>24.0</td>
<td>36.81</td>
<td>quiet</td>
<td>single, broad</td>
<td>1.11(1)</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>PSR J1617-5055</td>
<td>69.0</td>
<td>8.0</td>
<td>37.20</td>
<td>very dim</td>
<td>single, broad</td>
<td>1.42(2)</td>
<td>no</td>
<td>?</td>
</tr>
<tr>
<td>PSR J1930+1852 (G54.1+0.3)</td>
<td>136</td>
<td>2.9</td>
<td>37.08</td>
<td>very dim</td>
<td>single, broad</td>
<td>1.21(1)</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>PSR J0205+6449 (3C58)</td>
<td>65.7</td>
<td>5.4</td>
<td>37.43</td>
<td>very dim</td>
<td>two sharp pulses</td>
<td>1.1(1)</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>PSR J2229+6114 (G106.6+2.9)</td>
<td>51.6</td>
<td>10.5</td>
<td>37.34</td>
<td>weak</td>
<td>two pulses</td>
<td>1.11(3)</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>AX J1838.0-0655</td>
<td>70.5</td>
<td>23.0</td>
<td>36.75</td>
<td>quiet</td>
<td>structured broad</td>
<td>1.12(1)</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>IGR J14003-6326</td>
<td>31.2</td>
<td>12.7</td>
<td>37.71</td>
<td>dim</td>
<td>broad</td>
<td>1.95(4)</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>IGR J18490-0000</td>
<td>38.5</td>
<td>42.8</td>
<td>36.99</td>
<td>quiet</td>
<td>broad</td>
<td>1.37(1)</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>PSR J0537-6910 (N157B)</td>
<td>16.1</td>
<td>4.9</td>
<td>38.69</td>
<td>quiet</td>
<td>single, sharp</td>
<td>1.57(1)</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>PSR J2022+3842 (G76.9+1.0)</td>
<td>48.6</td>
<td>8.9</td>
<td>37.47</td>
<td>very dim</td>
<td>two sharp pulses</td>
<td>1.20(2)</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>PSR J1813-1749 (G12.82-0.02)</td>
<td>44.7</td>
<td>5.6</td>
<td>37.75</td>
<td>quiet</td>
<td>single, broad</td>
<td>1.30(3)</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

New candidate: PSR J1640-465  206 ms, 3.3 kyr, 36.64, single broad, 1.2, no, yes (HESS J1640-465)

(NuStar discovery; Gotthelf et al. 2014)
PSR B0833-45: Pulse profile morphology from radio $\rightarrow$ high energy $\gamma$-rays

Very complex pulse profile with many emission structures!

ISGRI: 6.1 Ms eff. Exp.
PSR B1509-58 update: CGRO BATSE, RXTE HEXTE & Fermi LAT

$\nu F_\nu$ spectrum peaks near 2.5 MeV
AX J1838.0-0655

- Discovered in 2008 as an energetic 70.5 ms X-ray pulsar using RXTE PCA data (ATEL #1392; Gotthelf & Halpern (2008))
- Associated with HESS J1837-069
- Characteristic age: 22.6 kyr
- Hard X-ray photon index $\Gamma \sim 1.36(2)$ at 14.2 keV (Kuiper & Hermsen 2014; in prep.)
- Since discovery RXTE monitoring ➞ pulsar ephemeris

Since its discovery a large timing glitch has been detected (Atel #2446; Kuiper & Hermsen)!
Total emission from AX J1838.0-0655

Suzaku XIS 0.7-10 keV (42.2 ks): $\Gamma=1.27\pm0.11$; Anada et al. (2009)
INTEGRAL ISGRI 20-300 keV : $\Gamma=1.72\pm0.07$; this work; consistent with Malizia et al. (2005)

Decoupling pulsed/DC spectra ➞ underlying PWN spectrum!
PSR J2229+6114: the energetic young pulsar in 3EG J2227+6122

- Discovered by Halpern et al. 2001 in unid. EGRET error region at radio freq. and at X-rays (ASCA): P = 51.6 ms; τ_c=10.5 kyr
  
  Bright PWN (see below)

- Pulsations, also detected now by AGILE and Fermi above 100 MeV: a broad asymmetric pulse

- Recent detection of extended TeV emission with Veritas (VER J2227+608) from near environment

Archival RXTE PCA/HEXTE data reveal pulsed emission up to ~30 keV using ~220 ks exposure with hard spectrum, photon index Γ = 1.11(3)
IGR J18490-0000

I) Chandra HRC-SI
Nov. 20, 2011 (25.1 ks)

II) Chandra ACIS-S
Nov. 16, 2012 (22.7 ks)

Goals:

1) Evidence for diffuse emission?

2) Pulsed fraction?

(reported; $P_f \sim 0.25$
PCA based; Gotthelf et al., 2011)

No pronounced diffuse emission seen in HRC-S data

$P_f = 0.77 +/- 0.04$
2 circular "bg" regions (r = 60") and 2 rectangular "diffuse" PWN emission extraction regions (150" x 65" and 75" x 37.5" minus 5" radius source region) :

Weak, hard PWN emission $\Gamma = 1.18 +/- 0.05$ 
about 5 x weaker than PSR emission

HE-spectrum (Total; unabs. )
ACIS-S (5" source): 1.15 +/- 0.02
EPIC MOS 1+2 : 1.13 +/- 0.01
EPIC Pn (SWM) : 1.23 +/- 0.01

Pulsed
EPIC Pn (SWM) : 1.14 +/- 0.01
Soft $\gamma$-ray pulsar characteristics

Spectral view (1 keV – 10 GeV)

Profile morphology:

- Single sharp pulse : #1
- Two (sharp) pulses : #4 (3 LAT PSR's)
- Multiple sharp : #1 (Vela; LAT)
- Single (structured) : #10 (1509-58;LAT)
- Broad pulse

Maximum luminosity at MeV energies!
Spin-down luminosity (non-recycled)

~50 x more energetic

Characteristic age/time scale

~10 x "younger"

Light grey: Fermi LAT pulsars (77 entries)
Dark grey: Soft $\gamma$-ray pulsars (16 entries)

Surface magnetic field strength

Comparable distributions!
Summary & Conclusions

- The number of pulsars detected at soft $\gamma$-rays has increased to 16 [+1]. Above 100 MeV now more than 117 pulsars detected by Fermi LAT, only 5 pulsars in both samples...

- The soft $\gamma$-ray pulsar population is younger and more energetic than the LAT one.

- Soft $\gamma$-ray pulsars reach max. luminosity at MeV energies, the LAT pulsars do so in GeV range.

- The large majority of the soft $\gamma$-ray pulsars has single broad (asymmetric/structured) pulses contrary to the LAT pulsars, showing mainly double pulses.

- Soft $\gamma$-ray pulsars are in general associated with bright X-ray/TeV PWNe.

- The current missions sensitive for hard X-rays are not / hardly sensitive enough to detect the "GeV-pulsars" ➞ need more sensitive missions (NuSTAR; Astro-H; AstroSat; LOFT; and MeV missions like e.g. DUAL, GRIPS).

- Open questions: Why no detection of pulsed non-thermal X-ray emission (>2 keV) from PSR J1119-6127, (1.6 kyr) PSR J1357-6429 (7.3 kyr) and PSR J1124-5916 (2.9 kyr), while we have Fermi LAT detections and TeV detections of two? Instead soft pulsed X-ray emission (< 2 keV; thermal?) has been detected...

  What about: PSR J1833-1034 (G21.5-0.9): LAT plus TeV/soft $\gamma$-ray (ISGRI) detection, but NO X-ray pulsations...

Fast and energetic radio pulsar: $P = 48.6$ ms,
$L_{sd} = 3.0 \times 10^{37}$ erg/s

Two sharp X-ray pulses at 0.484(1)
(see also Arumugasamy et al. 2013)

Hard pulsed X-ray spectrum: $\Gamma = 1.20(2)$
A new candidate soft $\gamma$-ray pulsar: PSR J1813-1749 in G12.82-0.02 and associated with HESS J1813-178 / IGR J18135-1751

- Putative pulsar and PWN discovered by Helfand et al. (2007) using 30 ks CXO ACIS data (15/09/2006; see left 2 panels).

  X-ray Spectra obtained for point-source ('PSR'; < 2"), Inner Nebula (6" x 8") and PWN (r = 80").

- An energetic 44.7 ms X-ray pulsar was detected by Gotthelf & Halpern (2009) using XMM-Newton EPIC-pn data from a 98 ks obs. performed on 27/03/2009.

  (broad pulse; hard spectrum > 2 keV)

- Additional XMM and CXO obs. taken in 2011/2012 yielded the spin-down:

  \[ L_{\text{sd}} = 5.6 \times 10^{37} \text{ erg/s} ; \tau = 5.6 \text{ kyr} \]

- Revisiting now 125.8 ks RXTE PCA data taken between 16-20 Nov. 2007 with only ONE operational PCU and at 30' offset angle.
A new candidate soft γ-ray pulsar: PSR J1813-1749 in G12.82-0.02 and associated with HESS J1813-178 / IGR J18135-1751

- Restricted period search using 2-20 keV PCA data yielded ~5σ signal (single trial) near predicted period!
- PCA pulsed spectrum (black) consistent with XMM-Newton pulsed spectrum (dark-orange), and >3σ signal for 10-20 keV energy band

Consistent HE-spectral picture!
Geometries of high-energy emission pulsar models

null charge surface \( \Omega \cdot B = 0 \)

closed field region

striped wind

\( \Rightarrow \) modelling with multiple beams is required, considering aberration and light-travel-time effects