Observations of “Soft” Gamma-Ray Pulsars with AGILE

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on behalf of the AGILE Pulsar WG

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AGILE

20 MeV - 50 GeV

The 30-100 MeV AGILE sensitivity is competitive (500 cm² eff. Area for timing).

Fermi

20 MeV - 300 GeV

The 1 GeV Fermi sensitivity is much better than the AGILE one.
New Gamma-Ray Pulsars

J2229+6114, J2021+3651, ...: Vela-like

B1509-58: High B pulsar

B1821-24: ms PSR in Globular Cluster

J1016-5857: possibly 3EG source

J1357-6429

J2043+2740: oldest gamma-ray pulsar

J1524-5625
$P \approx 150 \text{ ms}$

$\dot{P} \approx 1.53 \times 10^{-12} \text{ s}^{-1}$

$\tau_{sd} \approx 1570 \text{ yrs}$

$\dot{E} \approx 1.8 \times 10^{37} \text{ erg s}^{-1}$

$B \approx 3.1 \times 10^{13} \text{ G}$
PSR B1509-58 with Comptel

Kuiper et al. 1999
PSR B1509-58 with AGILE (1)


Fig. 2. — Light curves of the pulsar PSR B1509−58 in different energy bands within a circular region of energy-dependent radius. From bottom to the top: COMPTEL 0.75–30 MeV; 100–30 MeV; 300 MeV < E < 1 GeV; E = 1 GeV; 30 MeV–100 MeV; 100 MeV–300 MeV; 300 MeV–1 GeV; 1 GeV–300 GeV energy bands are presented. Two cycles are shown.
The "soft" $\nu$-pulsar B1509-58

AGILE (Pilia et al. 2010)

Fermi (Abdo et al. 2010)
PSR B1509-58 with AGILE (2)

Pilia et al. 2010
- Third order QED process

- Forbidden in vacuum

- For \( B \leq B_{cr} \) (\( B_{B1509} = 3.1 \times 10^{13} \text{ G} \)) it takes place BEFORE the threshold for pair production

- \( \gamma \to \gamma \gamma \) so that high energy emission (> some GeVs) is inhibited
Photon Splitting - Pair Production

\[ F(E) \propto E^{-\alpha} \exp[-(E/E_C)] \]
\[ \alpha = 1.87 \pm 0.09 \]

\[ \varepsilon_{esc}^{sat} \approx 0.077 (B' \sin \theta_{kB}, 0)^{-6/5} \]

\[ B' = B / B_{cr} \]
\[ \theta_{kB} = \text{angle between the photon momentum and the magnetic field vectors} \]

- Given the observed cutoff energy \( E_C = 81 \pm 20 \text{ MeV} \), the corresponding magnetic field is \( B' = 0.3 \). This implies emission at height \( h \approx 1.3 R_{NS} \) above the PC, where the pair production ensues.

Pilia et al. 2010
Alternative scenarios

**OUTER GAP**

- Zhang & Cheng 2000
  - $\alpha \approx 60^\circ$
  - $\zeta \approx 75^\circ$

**TWO POLE CAUSTIC GAP**

- Watters et al. 2009
  - $\alpha = 15^\circ$ to $90^\circ$

- Romani & Watters 2010
  - $\alpha \approx 35^\circ$
  - $\zeta \approx 90^\circ$

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FIG. 9. — Collection of sample light curves for the TPC model. Four select $w$ (values in bottom right panel) are shown for each panel; the radio pole has closest approach at phase=0. The values for the number of all peaks, the number of broad peaks and the minimum peak separation (in %) are indicated by each curve. Intensities are normalized to pulse maximum.

FIG. 14. — Light curves for the Two Pole Caustic (TPC) model. Each panel shows curves for four values of the gap width $w$. The curves are labelled with the number of major peaks and the peak separation, in percent.
### Geometry Constraints

<table>
<thead>
<tr>
<th>OUTER GAP</th>
<th>TWO POLE CAUSTIC GAP</th>
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<tbody>
<tr>
<td>$\alpha \approx 60^\circ$</td>
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- $\alpha$ = magnetic inclination
- $\zeta$ = viewing angle

- $\alpha < 60^\circ$ at the $3\sigma$ confidence level (Crawford et al. 2001)

- If $\zeta > 70^\circ$ (Melatos 1997) then $\alpha > 30^\circ$ at the $3\sigma$ level

- For these values, however, the Melatos model for the spin down of an oblique rotator predicts a braking index $n > 2.86$ slightly inconsistent with the observed value $n = 2.839(3)$ (Livingstone et al. 2005)
A Similar Case: PSR B0656+14

\[ E_C = 700 \text{ MeV} \]

Weltevrede et al. 2010
New Results from Fermi

$E < 500$ MeV

$E < 300$ MeV

$E < 150$ MeV
Interpretation

Our observations are compatible with emission from the polar cap regions powered by photon splitting cascades.

This likely interpretation could represent the first physical measurement ever made related to the QED photon splitting process.

The fact that PC emission at HE appears rare might be explained by the requirement that a number of conditions concur to have low magnetosphere emission, e.g. an aligned geometry and high magnetic fields.

New class of “soft” gamma-ray pulsars?
PSR J1846-0258 in SNR Kes 75

\[ P \approx 324 \text{ ms} \]

\[ \dot{P} \approx 7 \times 10^{-12} \text{ s s}^{-1} \]

\[ \tau_{sd} \approx 723 \text{ yrs} \]

\[ \dot{E} \approx 8 \times 10^{36} \text{ erg s}^{-1} \]

\[ B \approx 4.9 \times 10^{13} \text{ G} \]

\[ B > B_{\text{critical}} \]
Pulsar vs Magnetar
AGILE Observations of PSR J1846-0258

Pilia et al., submitted to ApJ
Spectrum of PSR J1846-0258

Kuiper & Hermsen 2009

Pilia et al., submitted
J1846-0258 vs J1119-6127

- High B \( (4.9 \times 10^{13}) \) G
- \( E_{\text{cutoff}} = 18(6) \) MeV
- No evidence for geometry
- Best explained by polar cap + photon splitting

- High B \( (7 \times 10^{13}) \) G
- \( E_{\text{cutoff}} \sim 1 \) GeV
- Close to orthogonal geometry
- Best explained by outer gap emission

Pilia et al. submitted

Parent et al. 2011
Diversity & Evolution

The lives of pulsars

KEY
- Regular pulsations
- Irregular pulsations
- No pulsations
- Radio emission
- X-ray emission
- X-ray outbursts
- Power pulsar wind nebulae
- Some of these objects (not all)

A pulsar’s magnetic field at birth and its age when astronomers observe it likely determines its classification. While each group has certain characteristics, not all objects in the group faithfully follow these traits. For example, there are two magnetars that exhibit radio emission, but do so with irregular pulsations. The X-ray bright magnetars typically produce regular signals.

Kaspi et al. 2010
P-Pdot Diagram for High B Pulsars

Kondratiev et al. 2010
Evolutive Path?

Braking Index: $n = \frac{\Omega \dot{\Omega}}{\Omega^2} \ll 3$

Frequent Glitch Activity

$B = 3.2 \times 10^{19} \sqrt{P \dot{P}}$

$\tau = \frac{1}{n - 1} \frac{P}{\dot{P}}$

Espinoza et al. 2011
Evolutive Path?

Braking Index: \( n = \frac{\Omega \ddot{\Omega}}{\dot{\Omega}^2} \ll 3 \)

Frequent Glitch Activity

\[ B = 3.2 \times 10^{19} \sqrt{P \dot{P}} \]

\[ \tau = \frac{1}{n - 1} \frac{P}{\dot{P}} \]

High B, small age \( \rightarrow \) MAGNETARS

Espinoza et al. 2011
Importance of the Toroidal Field

PSR J1846-0258

SGR 0418+5729

Rea et al. 2010
Interpretation

A progressive alignment of the spin and magnetic axes (w&j07) could trigger changes in the toroidal field structure which would explain the magnetic activity and consequent observed decrease in $n$ (lkjg11).

A magnetic field above the quantum critical value is observed and an aligned geometry is proposed.

Our observations are compatible with emission from the polar cap regions powered by photon splitting cascades also responsible for the absence of radio emission (high B).

Are we witnessing a conversion?
AGILE data on 12 Pulsars published so far including >40% of AGILE Team pulsar targets (AO1 & AO2)

**Future Work**

AGILE detected about 20 gamma-ray pulsars and tens of candidates from the spatial analysis

AGILE Pulsar Catalog in preparation

Pilia et al., in prep.
Thank you!