Millisecond Pulsars and the Galactic Center Excess

Peter L. Gonthier

Hope College

13th Rencontres du Vietnam
Exploring the Dark Universe
ICISE
Quy Nhom, Vietnam
1. Pulsar Zoo
2. Millisecond Pulsars
3. Population Synthesis
4. Globular Clusters
5. Galactic Center Excess
Collaborators

Population Synthesis of Millisecond Pulsars from the Galactic Disk and Bulge

- Alice Harding & Elizabeth Ferrara — NASA Goddard Space Flight Center
- Sara Frederick — University of Maryland
- Victoria Mohr — Washington and Jefferson College
- Yew-Meng Koh — Hope College
Fifty Years...July 1967— Jocelyn Bell and Anthony Hewish

Pulsar Zoo with over 2530 subjects
Radiation Models

- Radio emission - core and cone beams
- $\gamma$-ray emission - Slot Gap Two Pole Caustic (TPC), Outer Gap (OG), and Pair Starved Polar Cap (PSPC)
- Phenomenological Luminosities

\[ L_\nu = f_\nu P_\nu^{\alpha_\nu} \dot{P}_\nu^{\beta_\nu} \text{ mJy} \cdot \text{kpc}^2 \cdot \text{MHz} \]
\[ L_\gamma = f_\gamma P_\gamma^{\alpha_\gamma} \dot{P}_\gamma^{\beta_\gamma} \text{ eV} \cdot \text{s}^{-1} \]

- Explore model free parameter space with Markov Chain Monte Carlo (MCMC) techniques.
γ-ray Emission in the Pulsar Magnetosphere

Possible sites of particle acceleration

In most of the magnetosphere
\[ E \cdot B = 0 \]

Deficient charge supply
\[ E \cdot B \neq 0 \]

Solve Poisson’s Eqn
\[ \nabla \cdot E_{\parallel} = 4\pi (\rho - \rho_{GJ}) \]
\textbf{\(\gamma\)-ray Sky Maps — Magnetic Inclination of 60°}

- **TPC** — Two Pole Caustic Model (Slot Gap) — geometric model — narrow emission along the last open field surface
- **OG** — Outer Gap Model — emission high in the magnetosphere with one pole contributing for a given \(\zeta\)
- **PSPC** — Pair Starved Polar Cap Model — emission from the entire open volume region above the polar cap
Fitting radio and $\gamma$-ray light curves of MSPs

High Altitude $\gamma$-ray Emission - Spectral Power of the Vela Pulsar

- $\frac{dN}{dE}$ — Photon Spectrum
- $\frac{dN}{dE} = E^\Gamma e^{-E/E_c}$
- $\Gamma = -1.51 \pm 0.01$
- $E_c = 2.89 \pm 0.09$ GeV
- Super-exponential cutoffs
- $\frac{dN}{dE} \propto e^{-(E/E_c)^b}$ with $b = 2$ excluded to $16\sigma$
- $\gamma$-ray emission occurs at high altitudes near the light cylinder in most cases of young pulsars

Population Synthesis of MSPs — Comparison Group

To tune unknown radio and \( \gamma \)-ray luminosity model parameters:

- *Fermi* First Point Source Catalog (Abdo et al. 2010) (1FGL) - 11 month viewing - 54 *Fermi* MSPs detected as point sources
- 13 radio surveys are included in the simulation - 92 radio MSPs
- Target birth rate of \( 4.5 \times 10^{-4} \) MSPs per century (Story, Gonthier, & Harding 2007, ApJ, 671, 713.) — 4.5 per Myr
- Normalization of the simulation - to simulate 92 radio MSPs and predict *Fermi* radio-loud MSPs for other viewing periods.
MC Results - Histograms of Radio Pulsars

- Number of Radio Pulsars vs. Log(Period) (s)
- Number of Radio Pulsars vs. Log(Period Derivative) (s/s)
- Number of Radio Pulsars vs. Log(S1400) (mJy)
- Number of Radio Pulsars vs. Galactic Latitude (degrees)
- Number of Radio Pulsars vs. Log(Characteristic Age) (yr)
- Number of Radio Pulsars vs. Log(Magnetic Field) (G)
- Number of Radio Pulsars vs. Log(Dispersion Measure) (pc/cm³)
- Number of Radio Pulsars vs. Galactic Longitude (degrees)

Legend:
- Detected
- Normal

Peter L. Gonthier (Hope College)
MC Results - Histograms of *Fermi* Pulsars

![Histograms of Fermi Pulsars](image)

- **Number of Fermi Pulsars**
  - Log(Period) (s)
  - Log(Period Derivative) (s/s)
  - Log(γ-ray Energy Flux) (eV·cm⁻²·s⁻¹)
  - Log(S₁₄₀₀) (mJy)
  - Log(Characteristic Age) (yr)
  - Log(Magnetic Field B) (G)
  - Log(Dispersion Measure) (pc·cm⁻³)
  - Log(γ-ray Luminosity) (erg·s⁻¹)

Legend:
- Detected
- TPC
- OG
- PSPC
MC Results - $\dot{P} - P$ diagram

54 Fermi Pulsars
11 months Detected

$10^{35}$, $10^{34}$, $10^{33}$, $E_{\text{dot}}$ (erg/s)

54 Fermi Pulsars
TPC Simulated

Radio Pulsars
Fermi Pulsars
## Predicted *Fermi*-LAT future detections

<table>
<thead>
<tr>
<th>Catalog</th>
<th>Observing Period</th>
<th>Detected</th>
<th>Simulated — radio-loud &amp; (radio-weak)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>TPC</td>
</tr>
<tr>
<td>BSL</td>
<td>3 months</td>
<td>13</td>
<td>27 (25)</td>
</tr>
<tr>
<td>1FGL</td>
<td>11 months</td>
<td>54</td>
<td>54 (50)</td>
</tr>
<tr>
<td>2FGL</td>
<td>2 years</td>
<td>68</td>
<td>80 (77)</td>
</tr>
<tr>
<td>3FGL</td>
<td>4 years</td>
<td>82</td>
<td>114 (117)</td>
</tr>
<tr>
<td></td>
<td>5 years</td>
<td></td>
<td>126 (132)</td>
</tr>
<tr>
<td></td>
<td>10 years</td>
<td></td>
<td>171 (180)</td>
</tr>
</tbody>
</table>

Point Source Catalogs are still incomplete!

<table>
<thead>
<tr>
<th>Catalog</th>
<th>Detected</th>
<th>Possible Additional MSPs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1FGL</td>
<td>54</td>
<td>10</td>
</tr>
<tr>
<td>2FGL</td>
<td>68</td>
<td>16</td>
</tr>
<tr>
<td>3FGL</td>
<td>82</td>
<td>16</td>
</tr>
</tbody>
</table>

(private communication, Elizabeth C. Ferrara)
47 Tuc seen in $\gamma$ rays for the first time by Fermi

- 47 Tuc is a steady $\gamma$-ray source - non-variable
- There are 23 known radio MSPs in 47 Tuc.
- Fermi does not see individual pulsations from MSP - too far - 4 kpc
- Using the ephemerides from 21 radio MSPs, Fermi saw no pulsations
- $\gamma$-ray flux is not due to a single MSP

Fermi Spectrum of 47 Tuc

![Graph showing the Fermi Spectrum of 47 Tuc with MSPs in 47 Tucanae and Simulated MSPs with different numbers of MSPs: 45 MSPs, 55 MSPs, and 35 MSPs.](image)
### Expected Number of MSPs from Abdo et al. 2010

<table>
<thead>
<tr>
<th>Name</th>
<th>$L_\gamma$ ($10^{34}$ erg $\cdot$ s$^{-1}$)</th>
<th>$N_{\text{MSPs}}$</th>
<th>Simulated $N_{\text{MSPs}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>47 Tucanae</td>
<td>$4.8^{+1.1}_{-1.1}$</td>
<td>$33^{+15}_{-15}$</td>
<td>$45 \pm 10$</td>
</tr>
<tr>
<td>Omega Cen</td>
<td>$2.8^{+0.7}_{-0.7}$</td>
<td>$19^{+9}_{-9}$</td>
<td>$20 \pm 5$</td>
</tr>
<tr>
<td>M 62</td>
<td>$10.9^{+3.5}_{-2.3}$</td>
<td>$76^{+38}_{-34}$</td>
<td>$85 \pm 20$</td>
</tr>
<tr>
<td>NGC 6388</td>
<td>$25.8^{+14.0}_{-10.6}$</td>
<td>$180^{+120}_{-100}$</td>
<td>$220^{+80}_{-70}$</td>
</tr>
<tr>
<td>Terzan 5</td>
<td>$25.7^{+9.4}_{-8.8}$</td>
<td>$180^{+100}_{-90}$</td>
<td>$200^{+20}_{-40}$</td>
</tr>
<tr>
<td>NGC 6440</td>
<td>$19.0^{+13.1}_{-5.0}$</td>
<td>$130^{+100}_{-60}$</td>
<td>$150 \pm 50$</td>
</tr>
<tr>
<td>M 28</td>
<td>$6.2^{+2.6}_{-1.8}$</td>
<td>$43^{+24}_{-21}$</td>
<td>$50 \pm 10$</td>
</tr>
<tr>
<td>NGC 6652</td>
<td>$7.8^{+2.5}_{-2.1}$</td>
<td>$54^{+27}_{-25}$</td>
<td>$70 \pm 30$</td>
</tr>
<tr>
<td>Average</td>
<td>$0.14^{+0.04}_{-0.03}$ per MSP</td>
<td>$89^{+24}_{-19}$</td>
<td>$105 \pm 13$</td>
</tr>
</tbody>
</table>
### Expected Number of MSPs from Abdo et al. 2010

<table>
<thead>
<tr>
<th>Name</th>
<th>$L_\gamma \left(10^{34} \text{ erg} \cdot \text{s}^{-1}\right)$</th>
<th>$N_{\text{MSPs}}$</th>
<th>Simulated $N_{\text{MSPs}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>47 Tucanae</td>
<td>$4.8_{-1.1}^{+1.1}$</td>
<td>$33_{-15}^{+15}$</td>
<td>$45 \pm 10$</td>
</tr>
<tr>
<td>Omega Cen</td>
<td>$2.8_{-0.7}^{+0.7}$</td>
<td>$19_{-9}^{+9}$</td>
<td>$20 \pm 5$</td>
</tr>
<tr>
<td>M 62</td>
<td>$10.9_{-2.3}^{+3.5}$</td>
<td>$76_{-34}^{+38}$</td>
<td>$85 \pm 20$</td>
</tr>
<tr>
<td>NGC 6388</td>
<td>$25.8_{-10.6}^{+14.0}$</td>
<td>$180_{-100}^{+120}$</td>
<td>$220_{-70}^{+80}$</td>
</tr>
<tr>
<td>Terzan 5</td>
<td>$25.7_{-8.8}^{+9.4}$</td>
<td>$180_{-90}^{+100}$</td>
<td>$200_{-40}^{+20}$</td>
</tr>
<tr>
<td>NGC 6440</td>
<td>$19.0_{-5.0}^{+13.1}$</td>
<td>$130_{-60}^{+100}$</td>
<td>$150 \pm 50$</td>
</tr>
<tr>
<td>M 28</td>
<td>$6.2_{-1.8}^{+2.6}$</td>
<td>$43_{-21}^{+24}$</td>
<td>$50 \pm 10$</td>
</tr>
<tr>
<td>NGC 6652</td>
<td>$7.8_{-2.1}^{+2.5}$</td>
<td>$54_{-25}^{+27}$</td>
<td>$70 \pm 30$</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>$0.14_{-0.03}^{+0.04}$</td>
<td>$89_{-19}^{+24}$</td>
<td>$105 \pm 13$</td>
</tr>
</tbody>
</table>

**Key Point**

expect $\sim 100$ MSPs per cluster
Galactic Center Excess

Ackermann et al. 2017
Dark Matter (DM) WIMP with mass $M_{\text{DM}}$ (20 – 60 GeV) annihilate via channels: $\tau^+\tau^-$ and $b^+b^-$ as suggested by this study.

$\gamma$-ray flux from WIMP is factorable into “particle physics” and “astrophysical” factors

$$\Phi (E_\gamma, b, \ell) = \Phi^{PP} E_\gamma \times J (b, \ell)$$ (2)

$$\Phi^{PP} (E_\gamma) = \frac{1}{2} \left( \frac{\langle \sigma v \rangle}{4\pi M_{\text{DM}}^2} \right) \sum_f \frac{dN_f}{dE_\gamma} B_f$$ (3)

$$J (b, \ell) = \int_0^\infty \rho (r)^2 \, ds$$ (4)

Navarro – Frenk – White

$$\rho (r) = \frac{\rho_s}{\left( \frac{r}{r_s} \right)^\gamma \left[ 1 + \left( \frac{r}{r_s} \right) \right]^{3-\gamma}}$$ (6)
\[ \langle \sigma v \rangle \sim 3 \times 10^{-26} \text{ cm}^3 \cdot \text{s}^{-1} \] Thermal annihilation cross section

Inner slope: \( \gamma = 1.2 \)

\[ E^2 \frac{dN}{dE} \text{ [GeV cm}^{-2} \text{ s}^{-1}] \]

- \( M_{DM} = 23.5 \text{ GeV}, 55\% \bar{b}b, 45\% \text{ leptons} \)
Galactic Center Excess - Gordon & Macias 2013

Galactic Center Excess

7° x 7°

45 months

TPC
Dark Matter WIMP Constraints


- Is the GCE a result of an unknown DM particle?
- Or a result of known astrophysical sources, MSPs, but have not been observed?
The GCE and Point Sources

Two independent studies conclude that point sources are responsible for the GCE.


The Source of MSPs in the Galactic Center

The dynamical inspiraling of globular clusters in a dynamical friction model.

- Gnedin et al. (2014) estimate that $2 \times 6 \times 10^7 \, M_\odot$ in globular clusters where dragged into a region of 3 to 5 pc (1.2’ to 2.0’) from the GC.
- Gnedin & Ostriker (1997) list the masses of 119 globular clusters giving an average mass of $3.8 \times 10^5 \, M_\odot$ per cluster.
- These studies would suggest that 50 to 160 globular clusters might have been captured by the GC.
- We estimated previously that there are about 100 MSPs per cluster.
- 100 captured globular clusters could provide 10,000 MSPs needed to account for the spectrum of the GCE.
- This is in agreement with our prediction.
The Future will tell!

10,000 MSPs simulated in the GC

MSPs in the Galactic Bulge

Number of Bulge MSPs

Log(Gamma-ray Flux) (cm$^{-2} \cdot s^{-1}$)

Log($S_{1400}$) (mJy)

3FGL

Gaussian

NFW

30 μJy

10,000 MSPs simulated in the GC
Acknowledgments

We also are grateful for the generous support of:

- The Michigan Space Grant Consortium
- The National Science Foundation under grant Nos. REU: PHY/DMR-1004811, and RUI: AST-1009731
- The *Fermi* Guest Investigator Program Cycle 3 under grant No. NNH09ZDA001N-FERMI3
- The NASA Astrophysics Theory and Fundamental Physics Program under the grant No. NNX13AO12G