Properties of Radio-quiet Gamma-ray pulsars

Jongsu Lee
Supervisor Prof. Hui
Population of Pulsars
In the 2PC, RL pulsars are defined by the detection of radio pulse above flux density limits of $S_{1400} = 30 \mu Jy$ at 1400 MHz.
After the launch of Fermi $\gamma$-ray Space Telescope

Abdo et al (2009)

Abdo et al (2013)
After the launch of Fermi γ-ray Space Telescope

Table 1. Pulsar varieties

<table>
<thead>
<tr>
<th>Category</th>
<th>Count</th>
<th>Sub-count</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Known rotation-powered pulsars (RPPs)</strong>&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2286</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RPPs with measured $P &gt; 0$</td>
<td>1944</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RPPs with measured $\dot{E} &gt; 3 \times 10^{33}$ erg s$^{-1}$</td>
<td>552</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Millisecand pulsars (MSPs, $P &lt; 16$ ms)</strong></td>
<td>292</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field MSPs</td>
<td>169</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MSPs in globular clusters</td>
<td>123</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field MSPs with measured $\dot{E} &gt; 3 \times 10^{33}$ erg s$^{-1}$</td>
<td>96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Globular cluster MSPs with measured $\dot{E} &gt; 3 \times 10^{33}$ erg s$^{-1}$</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Gamma-ray pulsars in this catalog</strong></td>
<td>117</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Young or middle-aged</td>
<td>77</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio-loud gamma-ray&lt;sup&gt;b&lt;/sup&gt;</td>
<td>42</td>
<td>36%</td>
<td></td>
</tr>
<tr>
<td>Radio-quiet gamma-ray</td>
<td>35</td>
<td>30%</td>
<td></td>
</tr>
<tr>
<td>Gamma-ray MSPs (isolated + binary)</td>
<td>(10+30) = 40</td>
<td>34%</td>
<td></td>
</tr>
<tr>
<td>Radio MSPs discovered in LAT sources with gamma-ray pulsations&lt;sup&gt;c&lt;/sup&gt;</td>
<td>46</td>
<td>34</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>Includes the 2193 pulsars, which are all RPPs, in the ATNF Pulsar Catalog (v1.46, Manchester et al. 2005), see [http://www.atnf.csiro.au/research/pulsar/psrcat](http://www.atnf.csiro.au/research/pulsar/psrcat) as well as more recent discoveries. D. Lorimer maintains a list of known field MSPs at [http://astro.phys.wvu.edu/GalacticMSPs/](http://astro.phys.wvu.edu/GalacticMSPs/).

<sup>b</sup>$S_{1400} > 30 \mu$Jy, where $S_{1400}$ is the radio flux density at 1400 MHz.

<sup>c</sup>Only 20 of the new radio MSPs showed gamma-ray pulsations when the dataset for this catalog was frozen.

Abdo et al(2013)
After the launch of Fermi $\gamma$-ray Space Telescope
Prior Researches

- New 8 RQ pulsars were detected by Marelli et al (2015).
- They fitted both RQ and RL pulsar distributions with single and double Gaussian models.
- An average $\log(F_\gamma/F_X)$ of $3.38 \pm 0.10$ for RQ pulsar with 0.62 null-hypothesis.
- Two gaussians at $1.81 \pm 0.11$ and $3.20 \pm 0.14$ with 0.38 null-hypothesis.

Prior Researches

- They performed a blind search for gamma-ray pulsars using the Fermi LAT data alone using all point sources from 3FGL catalog.
- There are 40 pulsating sources and 26 RQ and 14 RL.
- There are no statistically significant differences in characteristic age, $\dot{P}$, spin-down luminosity, gamma-ray luminosity and galactic coordinates.
- The rotation period histograms are marginally different with $2.4\sigma$ statistical significance.

Sokolova & Rubtsov (2016)

FIG. 4. Distributions of the rotation period $P$ for radio-loud and radio-quiet pulsars. The two distributions are compatible with KS probability 1.5%.
Motivation & Purpose

- Thanks to prior researches, the difference between RQ and RL result geometry.
- Confirm the possibility for difference of their physical properties. (ex: $B_S$, $B_{LC}$, spectral parameters, etc)
- Data sample is increased by utilizing 2$^{nd}$ Fermi LAT Catalog (2PC) and 3$^{rd}$ Fermi LAT Source Catalog (3FGL).
- Our data set include all data samples of prior researches.
- To perform the investigation of deeper parameters for pulsar nature.
How to collect data

- $B_S = 3.2 \times 10^{19} \sqrt{P \dot{P}}$
  \[ \approx 10^{12} G \left( \frac{\dot{P}}{10^{-15}} \right)^{1/2} \left( \frac{P}{\Omega} \right)^{1/2} \]
- $B_{LC} = B_S \left( \frac{\Omega R}{c} \right)^3$
  \[ \approx 9.2 G \left( \frac{P}{S} \right)^{-5/2} \left( \frac{\dot{P}}{10^{-15}} \right)^{1/2} \]

where $P$ is the rotational period, $\dot{P}$ is the period derivative, $\Omega = 2\pi/P$ is the rotational angular frequency, $R$ is the neutron star radius with assuming 10 km.
How to collect data
KS & AD test

- Kolmogorov-Smirnov (KS) test is widely used to test whether two unbinned distributions are different.

- Anderson-Darling (AD) test is more sensitive to identify the difference locates at the edges of the distribution or when these two distributions are crossed.
Results

Hui et al. 2017
Results

Such differences can be explained in the context of outer gap model by the geometric effect and the rotational period.

By assuming:

1) The gamma-ray are originated from the outer gap
2) The X-ray are originated from the polar cap due to backflow current heating
3) The open angle of the radio emission cone depends on $P^{-1/2}$
Result — Curve Significance

- Depends on how well the gamma-ray spectra can discriminate whether Power-Law and Power-Law with Exponential cut off.
- RL pulsars can be easily detected.
- In order to test the robustness, we alleviate this possible selection effect by re-running the AD-test on the pulsars detected at a level $> 10\sigma$ (i.e. $TS > 100$ in 3FGL).
- RQ pulsars satisfy and the sample size of RL pulsars is reduced to 29.
- In this case, p-value of AD-test is marginally 3 sigma, 0.003.
To account for the difference of gamma-ray spectral curvature, we speculate that inverse Compton process may play a role in high energy photon production.

RL pulsars generally have wider radio cones size.

Part of radio emission with frequency >100 MHz may get into the outer gap and IC scatter in GeV regime.

A shortage of photons for RQ produced at higher energies through IC process.
Result — Magnetic filed strength at stellar surface

- While we do not find any difference of $B_S$, the distributions of the $B_{LC}$ are found to be different.
- Both parameters are a function of $P$ and $\dot{P}$.
- To investigate if the $B_{LC}$ difference is caused by their rotational parameters, we have also applied the AD test for $P$ and $\dot{P}$. 
Result – Magnetic filed strength at light cylinder

- Marginal difference of P between this two population (p-value~0.006).
- To estimate the impact of this possible selection effect in P and $B_{LC}$, we re-run the AD test for the pulsars detected in the blind search by Sokolova & Rubtsov.
- We found that the statistical significance for the difference in P is not undermined.
- For $B_{LC}$, we found the statistical significance for the difference may drop to ~2.5σ.
- Since $B_{LC} \propto B_S$ and $P^{-3}$, Blc is more influenced by period.
Result — Spin-down power energy

- P-value is 0.003
- Since $\dot{E} \sim \dot{P} P^{-3}$, $\dot{E}$ is influenced by period.
Assumption that the X-rays are coming from the regions near the polar cap.

- $F_X^{PC} \propto \cos \theta$, where $\theta$ is angle between the magnetic axis and the viewing angle.
- RL pulsars should have smaller $\theta$ than those RQ pulsars.
- From observations and simulations (e.g. Takata, Wang and Cheng 2011), the difference in the gamma-ray flux distributions between RL and RQ pulsars is not enough large.
Results for correlation

- The aforementioned IC scenario can also provide a possible way to account for this phenomena.
- $E_{\text{cut}}$ might be determined by IC scattering between the radio emission and the primary positrons/electrons in the outer gap.
- If the open angle of the radio cone is larger, such effect can be enhanced.

$E_{\text{cut}} = (-1.74 \pm 0.36) + (1.15 \pm 0.11) \log B_{LC}$
Summary

- We have performed a detailed statistical analysis to probe the physical nature of RL and RQ gamma-ray pulsars.

- By comparing the cumulative distributions of selected parameters, we have identified the possible differences between these two populations.

- We found that the gamma-ray spectral curvature of RQ pulsars can be larger than that of RL pulsars.

- While the surface magnetic field strength $B_s$ has a similar distribution in both populations, their magnetic field strength at the light cylinder $B_{LC}$ are found to be different.

- Because we can found the difference of period cumulative distribution between RQ and RL.

- $F_\gamma/F_X$ of RQ population should be larger than the RL population.

- While we did not find correlation between $E_{\text{cut}}$ and $B_{LC}$ for RL population, we found strong positive correlation between $E_{\text{cut}}$ and $B_{LC}$ for RQ population.
Future work

- Since new source is continuously detected, we can again try to perform the empirical statistical analysis.

- The number of gamma-ray pulsar is more updated 211.

- Ultimately, we can pursue the correct and best result.

- Additionally, these methods can be adopted for the other populations.
Einstein@Home discovers a radio-quiet gamma-ray millisecond pulsar


Millisecond pulsars (MSPs) are old neutron stars that spin hundreds of times per second and appear to pulsate as their emission beams cross our line of sight. To date, radio pulsations have been detected from all rotation-powered MSPs. In an attempt to discover radio-quiet gamma-ray MSPs, we used the aggregated power from the computers of tens of thousands of volunteers participating in the Einstein@Home distributed computing project to search for pulsations from unidentified gamma-ray sources in Fermi Large Area Telescope data. This survey discovered two isolated MSPs, one of which is the only known rotation-powered MSP to remain undetected in radio observations. These gamma-ray MSPs were discovered in completely blind searches without prior constraints from other observations, raising hopes for detecting MSPs from a predicted Galactic bulge population.
Thanks to your attention.

Q & A