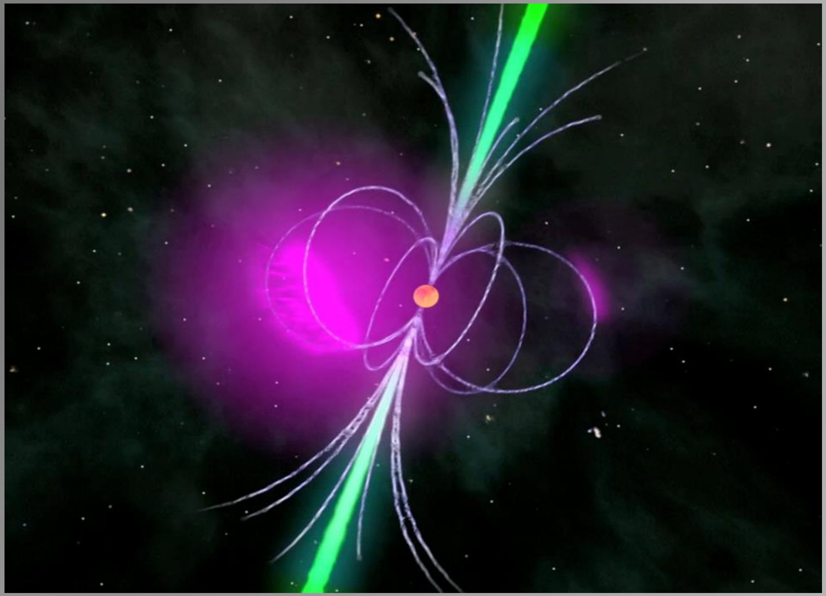
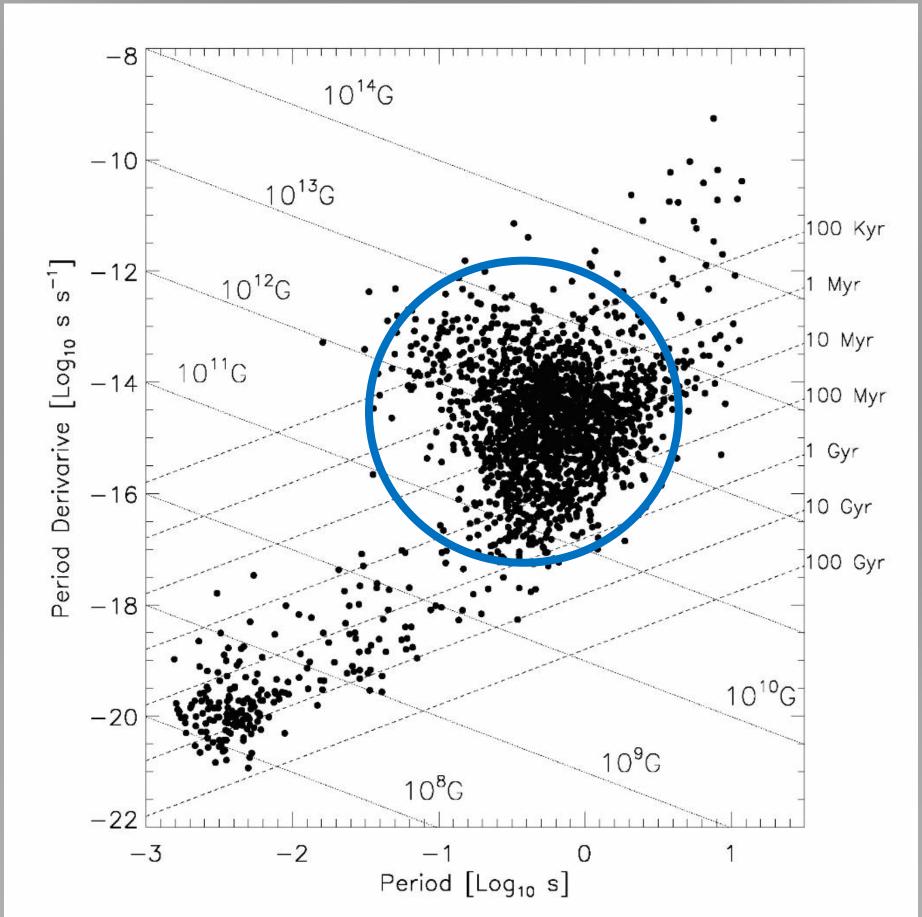
Properties of Radio-quiet Gamma-ray pulsars

Jongsu Lee

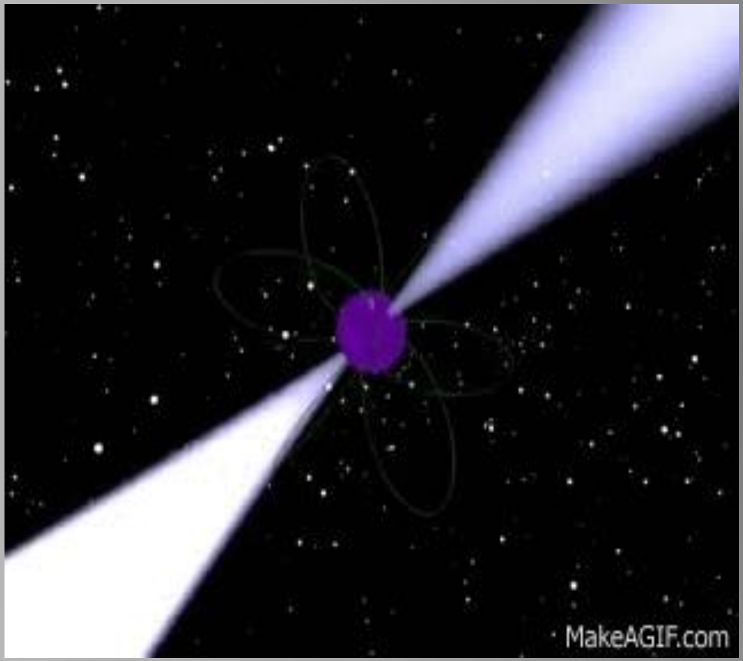
Supervisor Prof. Hui

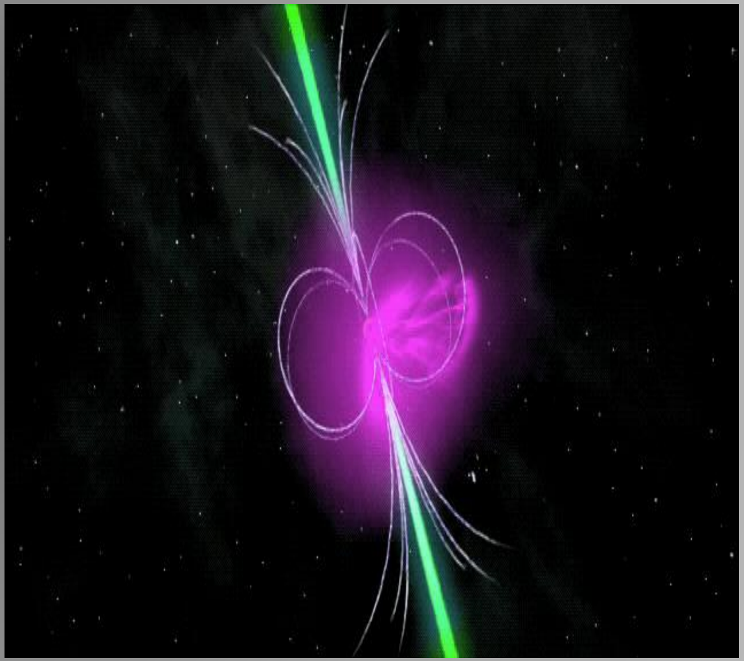


Population of Pulsars



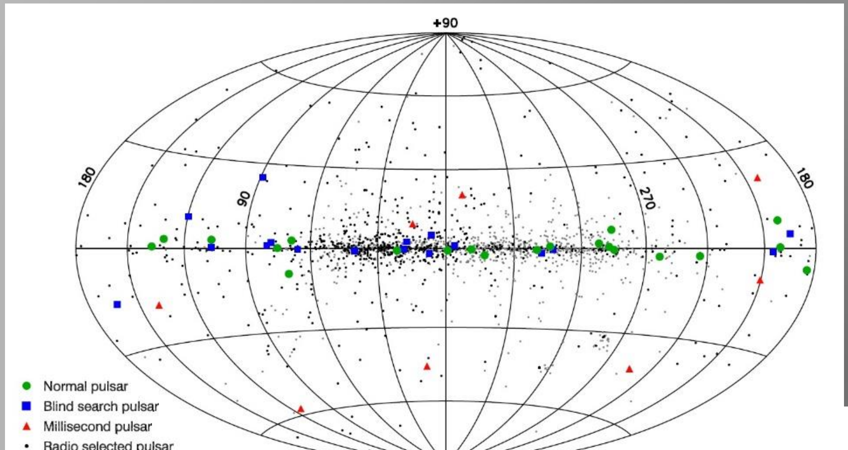
Radio-quiet vs Radio-loud



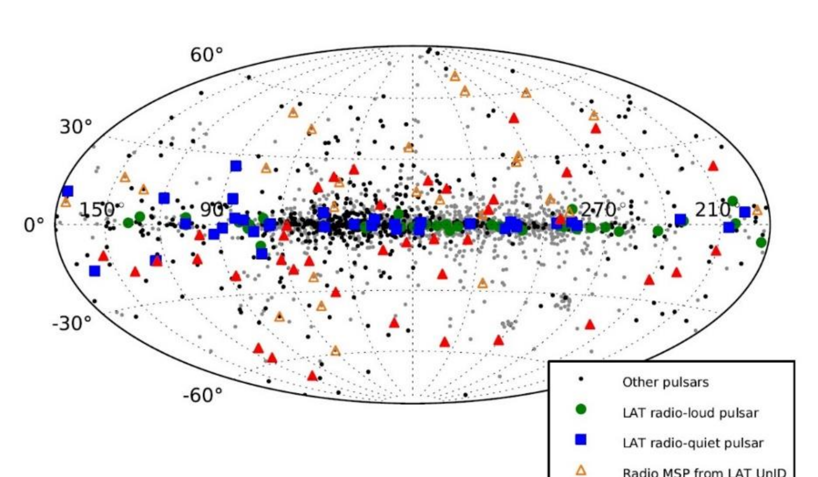


- In the 2PC, RL pulsars are defined by the detection of radio pulse above flux density limits of $S_{1400} = 30\mu Jy \ at \ 1400 \ MHz.$

After the launch of Fermi γ-ray Space Telescope



Abdo et al(2009)



Abdo et al(2013)

After the launch of Fermi γ-ray Space Telescope

Table 1. Pulsar varieties

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

[a] 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, as well as more recent discoveries. D. Lorimer maintains a list of known field MSPs at http://astro.phys.wvu.edu/GalacticMSPs/.

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

[c] 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 γ-ray Space Telescope

Pages / Fermi LAT Multiwavelength Coordinating Group

Public List of LAT-Detected Gamma-Ray Pulsars

Created by Paul Ray, last modified on Feb 21, 2018

The following is a compilation of all publicly-announced gamma-ray pulsars detected using the Fermi LAT. Each of the detections has been vetted by the LAT team, typically requiring a pulsed-detection significance of at least 4 sigma before announcement. We attempt to ensure that the information presented here is correct, but we strongly encourage users to consult the cited literature as the definitive source of information. Note that this list does **not** include all pulsars found in radio searches of LAT sources or other radio pulsars associated with LAT sources **unless** gamma-ray pulsations have been detected. To prevent inadvertent disclosure of private information, Edot column is only populated for pulsars whose discoveries have already been published, not just announced at a conference. Another warning: Edots in this list are NOT corrected for the Shklovskii effect.

Timing models (i.e. par files) for most published gamma-ray pulsars are available from the FSSC at this page . And, a list of all LAT published papers is available here . **NB**: When referencing particulars of any individual published pulsar, *please* cite the original papers and *not* this URL.

Last Updated: 2018 February 21
everything below this line is machine-generated

Summary Statistics

Total number of pulsars: 211

- Young, radio selected : 55
- Young, gamma selected : 55
- Young, X-ray selected : 5
- Total number young PSRs : 115
- MSP, radio selected : 95
- MSP, gamma selected : 1
- Total number of MSPs : 96
- Total number of binaries : 78
- Found in radio searches of LAT sources : 57
- EGRET/COMPTEL pulsars: 7

Prior Researches

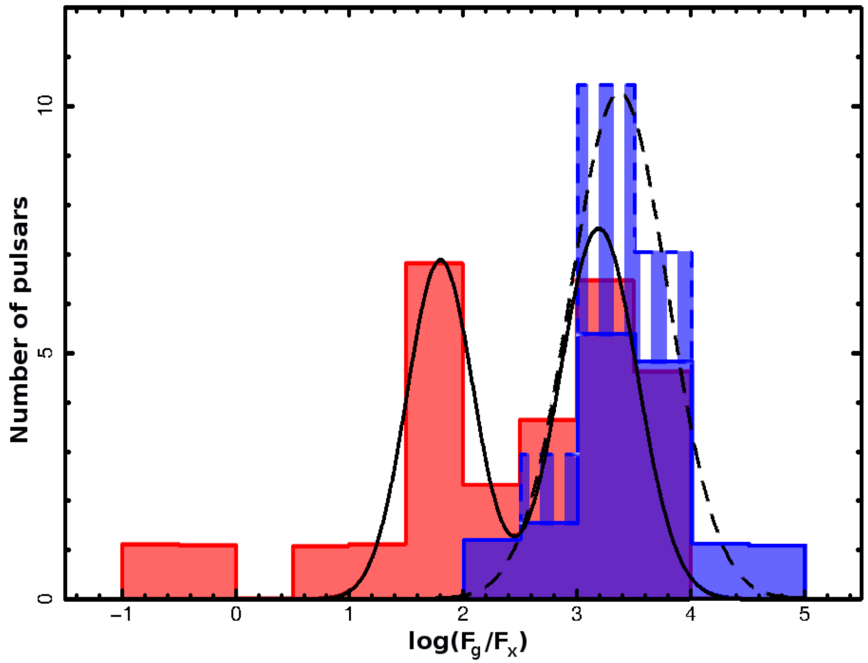


Fig. 2.— Histogram of the logarithm of the γ–to–X-ray flux ratio (F_γ/F_X) of LAT pulsars with high-confidence X-ray detections, as defined in Figure 3 of Marelli et al. (2011). Histograms for RL and RQ pulsars are shown in red and blue, respectively. The increment to the radio-quiet pulsar histogram for the eight pulsars that we detected in the X rays for the first time is shown in dashed blue and is added to the histogram of previously-known radio-quiet pulsars. For these pulsars, we used the results of the PL fits to compute the F_X values. The continuous and dashed lines report the best gaussian fit for the RL and RQ distributions, respectively.

Marelli et al (2015)

- 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 $\mathrm{Log}(F_\gamma/F_X)$ of 3.38 ± 0.10 for RQ pulsar with 0.62 null-hypothesis.
- Two gaussians at 1.81 ± 0.11 and 3.20 ± 0.14 with 0.38 null-hypothesis.

Prior Researches

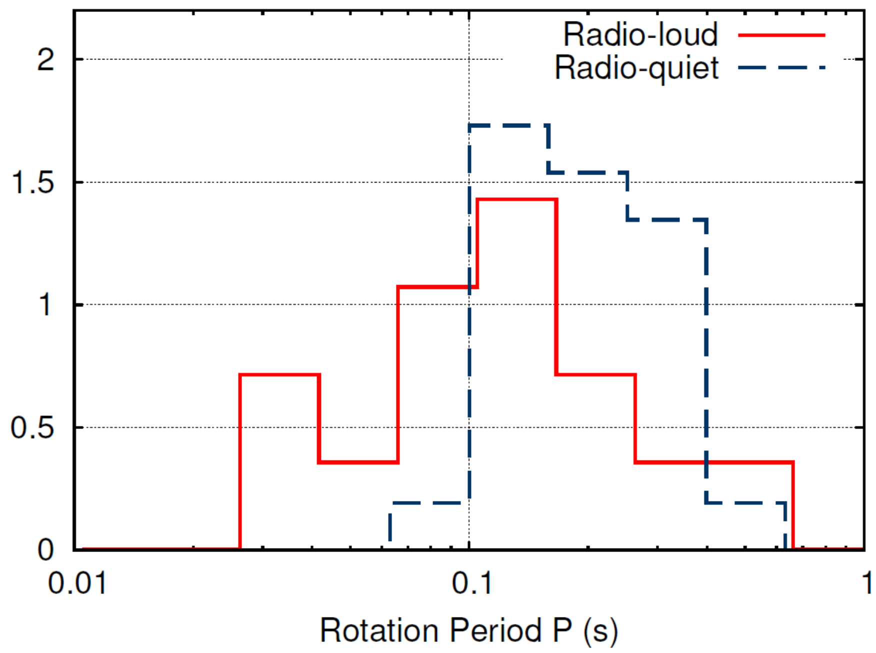


FIG. 4. Distributions of the rotation period P for radio-loud and radio-quiet pulsars. The two distrubutions are compatible with KS probability 1.5%.

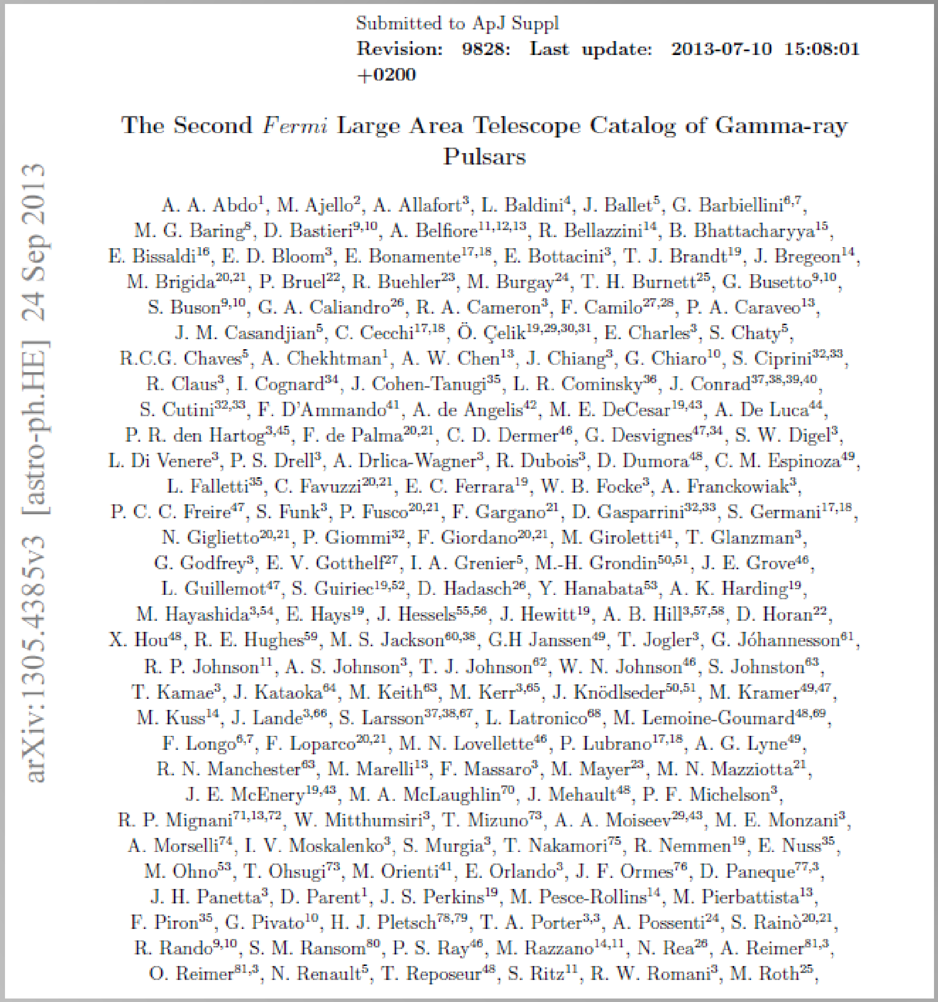
Sokolova & Rubtsov (2016)

- 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 2.4σ statistical significance.

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 2nd Fermi LAT Catalog (2PC) and 3rd 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



Submitted to ApJ Suppl
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arXiv:1305.4385v3 [astro-ph.HE] 24 Sep 2013

The Second *Fermi* Large Area Telescope Catalog of Gamma-ray Pulsars

A. A. Abdo[1], M. Ajello[2], A. Allafort[3], L. Baldini[4], J. Ballet[5], G. Barbiellini[6,7], M. G. Baring[8], D. Bastieri[9,10], A. Belfiore[11,12,13], R. Bellazzini[14], B. Bhattacharyya[15], E. Bissaldi[16], E. D. Bloom[3], E. Bonamente[17,18], E. Bottacini[3], T. J. Brandt[19], J. Bregeon[14], M. Brigida[20,21], P. Bruel[22], R. Buehler[23], M. Burgay[24], T. H. Burnett[25], G. Busetto[9,10], S. Buson[9,10], G. A. Caliandro[26], R. A. Cameron[3], F. Camilo[27,28], P. A. Caraveo[13], J. M. Casandjian[5], C. Cecchi[17,18], Ö. Çelik[19,29,30,31], E. Charles[3], S. Chaty[5], R.C.G. Chaves[5], A. Chekhtman[1], A. W. Chen[13], J. Chiang[3], G. Chiaro[10], S. Ciprini[32,33], R. Claus[3], I. Cognard[34], J. Cohen-Tanugi[35], L. R. Cominsky[36], J. Conrad[37,38,39,40], S. Cutini[32,33], F. D'Ammando[41], A. de Angelis[42], M. E. DeCesar[19,43], A. De Luca[44], P. R. den Hartog[3,45], F. de Palma[20,21], C. D. Dermer[46], G. Desvignes[47,34], S. W. Digel[3], L. Di Venere[3], P. S. Drell[3], A. Drlica-Wagner[3], R. Dubois[3], D. Dumora[48], C. M. Espinoza[49], L. Falletti[35], C. Favuzzi[20,21], E. C. Ferrara[19], W. B. Focke[3], A. Franckowiak[3], P. C. C. Freire[47], S. Funk[3], P. Fusco[20,21], F. Gargano[21], D. Gasparrini[32,33], S. Germani[17,18], N. Giglietto[20,21], P. Giommi[32], F. Giordano[20,21], M. Giroletti[41], T. Glanzman[3], G. Godfrey[3], E. V. Gotthelf[27], I. A. Grenier[5], M.-H. Grondin[50,51], J. E. Grove[46], L. Guillemot[47], S. Guiriec[19,52], D. Hadasch[26], Y. Hanabata[53], A. K. Harding[19], M. Hayashida[3,54], E. Hays[19], J. Hessels[55,56], J. Hewitt[19], A. B. Hill[3,57,58], D. Horan[22], X. Hou[48], R. E. Hughes[59], M. S. Jackson[60,38], G.H Janssen[49], T. Jogler[3], G. Jóhannesson[61], R. P. Johnson[11], A. S. Johnson[3], T. J. Johnson[62], W. N. Johnson[46], S. Johnston[63], T. Kamae[3], J. Kataoka[64], M. Keith[63], M. Kerr[3,65], J. Knödlseder[50,51], M. Kramer[49,47], M. Kuss[14], J. Lande[3,66], S. Larsson[37,38,67], L. Latronico[68], M. Lemoine-Goumard[48,69], F. Longo[6,7], F. Loparco[20,21], M. N. Lovellette[46], P. Lubrano[17,18], A. G. Lyne[49], R. N. Manchester[63], M. Marelli[13], F. Massaro[3], M. Mayer[23], M. N. Mazziotta[21], J. E. McEnery[19,43], M. A. McLaughlin[70], J. Mehault[48], P. F. Michelson[3], R. P. Mignani[71,13,72], W. Mitthumsiri[3], T. Mizuno[73], A. A. Moiseev[29,43], M. E. Monzani[3], A. Morselli[74], I. V. Moskalenko[3], S. Murgia[3], T. Nakamori[75], R. Nemmen[19], E. Nuss[35], M. Ohno[53], T. Ohsugi[73], M. Orienti[41], E. Orlando[3], J. F. Ormes[76], D. Paneque[77,3], J. H. Panetta[3], D. Parent[1], J. S. Perkins[19], M. Pesce-Rollins[14], M. Pierbattista[13], F. Piron[35], G. Pivato[10], H. J. Pletsch[78,79], T. A. Porter[3,3], A. Possenti[24], S. Rainò[20,21], R. Rando[9,10], S. M. Ransom[80], P. S. Ray[46], M. Razzano[14,11], N. Rea[26], A. Reimer[81,3], O. Reimer[81,3], N. Renault[5], T. Reposeur[48], S. Ritz[11], R. W. Romani[3], M. Roth[25],

- $B_S = 3.2 \times 10^{19}\sqrt{P\dot{P}}$
  $\cong 10^{12} G\, (\frac{\dot{P}}{10^{-15}})^{1/2} (\frac{P}{s})^{1/2}$
- $B_{LC} = B_S (\frac{\Omega R}{c})^3$
  $\cong 9.2 G\, (\frac{P}{s})^{-5/2} (\frac{\dot{P}}{10^{-15}})^{1/2}$

, 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

Accepted for Publication in ApJS

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Fermi Large Area Telescope Third Source Catalog

F. Acero[1], M. Ackermann[2], M. Ajello[3], A. Albert[4], W. B. Atwood[5], M. Axelsson[6,7],
L. Baldini[8,4], J. Ballet[1,9], G. Barbiellini[10,11], D. Bastieri[12,13], A. Belfiore[14], R. Bellazzini[15],
E. Bissaldi[16], R. D. Blandford[4], E. D. Bloom[4], J. R. Bogart[4], R. Bonino[17,18], E. Bottacini[4],
J. Bregeon[19], R. J. Britto[20], P. Bruel[21], R. Buehler[2], T. H. Burnett[22,23], S. Buson[12,13],
G. A. Caliandro[4,24], R. A. Cameron[4], R. Caputo[5], M. Caragiulo[16], P. A. Caraveo[14],
J. M. Casandjian[1], E. Cavazzuti[25,26], E. Charles[4], R.C.G. Chaves[19], A. Chekhtman[27],
C. C. Cheung[28], J. Chiang[4], G. Chiaro[13], S. Ciprini[25,29,30], R. Claus[4], J. Cohen-Tanugi[19],
L. R. Cominsky[31], J. Conrad[32,33,34,35], S. Cutini[25,30,29], F. D'Ammando[36,37], A. de Angelis[38],
M. DeKlotz[39], F. de Palma[16,40], R. Desiante[10,41], S. W. Digel[4,42], L. Di Venere[43],
P. S. Drell[4], R. Dubois[4], D. Dumora[44], C. Favuzzi[43,16], S. J. Fegan[21], E. C. Ferrara[45],
J. Finke[28], A. Franckowiak[4], Y. Fukazawa[46], S. Funk[47], P. Fusco[43,16], F. Gargano[16],
D. Gasparrini[25,30,29], B. Giebels[21], N. Giglietto[43,16], P. Giommi[25], F. Giordano[43,16],
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L. Guillemot[48,49], S. Guiriec[45,50], D. Hadasch[51], A. K. Harding[45], E. Hays[45],
J.W. Hewitt[52,53], A. B. Hill[54,4], D. Horan[21], G. Iafrate[10,55], T. Jogler[4], G. Jóhannesson[56],
R. P. Johnson[5], A. S. Johnson[4], T. J. Johnson[27], W. N. Johnson[28], T. Kamae[57],
J. Kataoka[58], J. Katsuta[46], M. Kuss[15], G. La Mura[13,51], D. Landriu[1], S. Larsson[6,33],
L. Latronico[17], M. Lemoine-Goumard[44], J. Li[59], L. Li[6,33], F. Longo[10,11], F. Loparco[43,16],
B. Lott[44], M. N. Lovellette[28], P. Lubrano[29,60], G. M. Madejski[4], F. Massaro[61], M. Mayer[2],
M. N. Mazziotta[16], J. E. McEnery[45,62], P. F. Michelson[4], N. Mirabal[45,50], T. Mizuno[63],
A. A. Moiseev[53,62], M. Mongelli[16], M. E. Monzani[4], A. Morselli[64], I. V. Moskalenko[4],
S. Murgia[65], E. Nuss[19], M. Ohno[46], T. Ohsugi[63], N. Omodei[4], M. Orienti[36], E. Orlando[4],
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S. Razzaque[20], A. Reimer[51,4], O. Reimer[51,4], T. Reposeur[44], L. S. Rochester[4],
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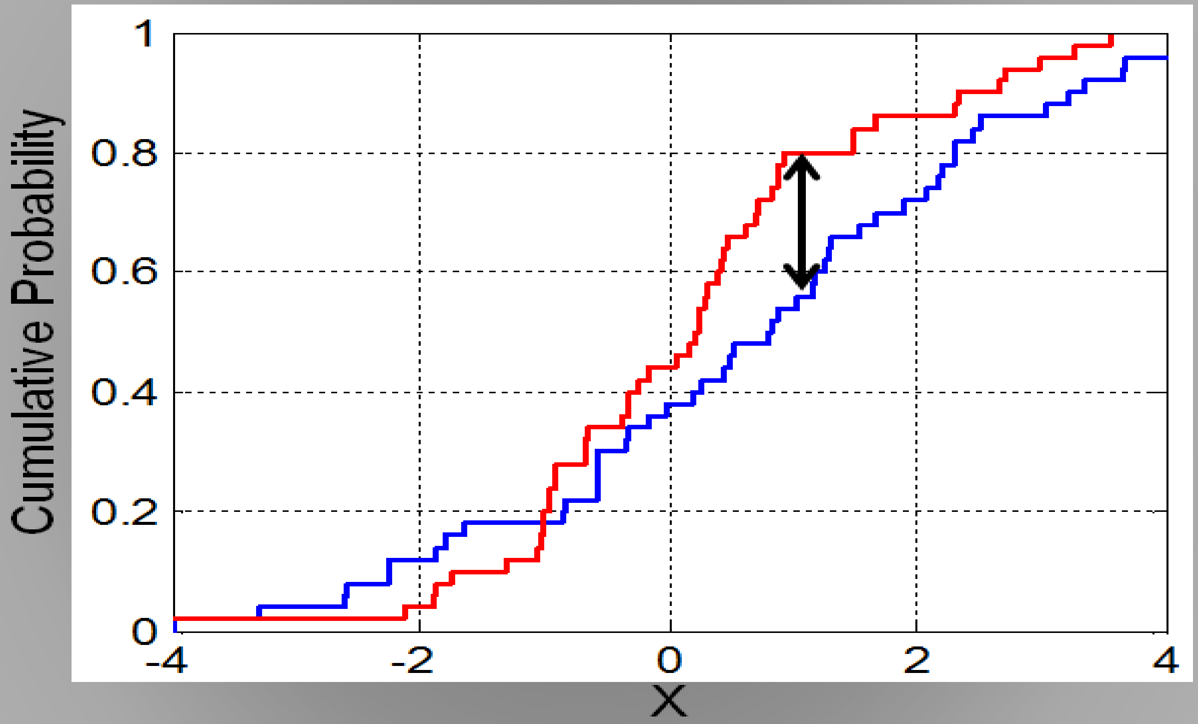
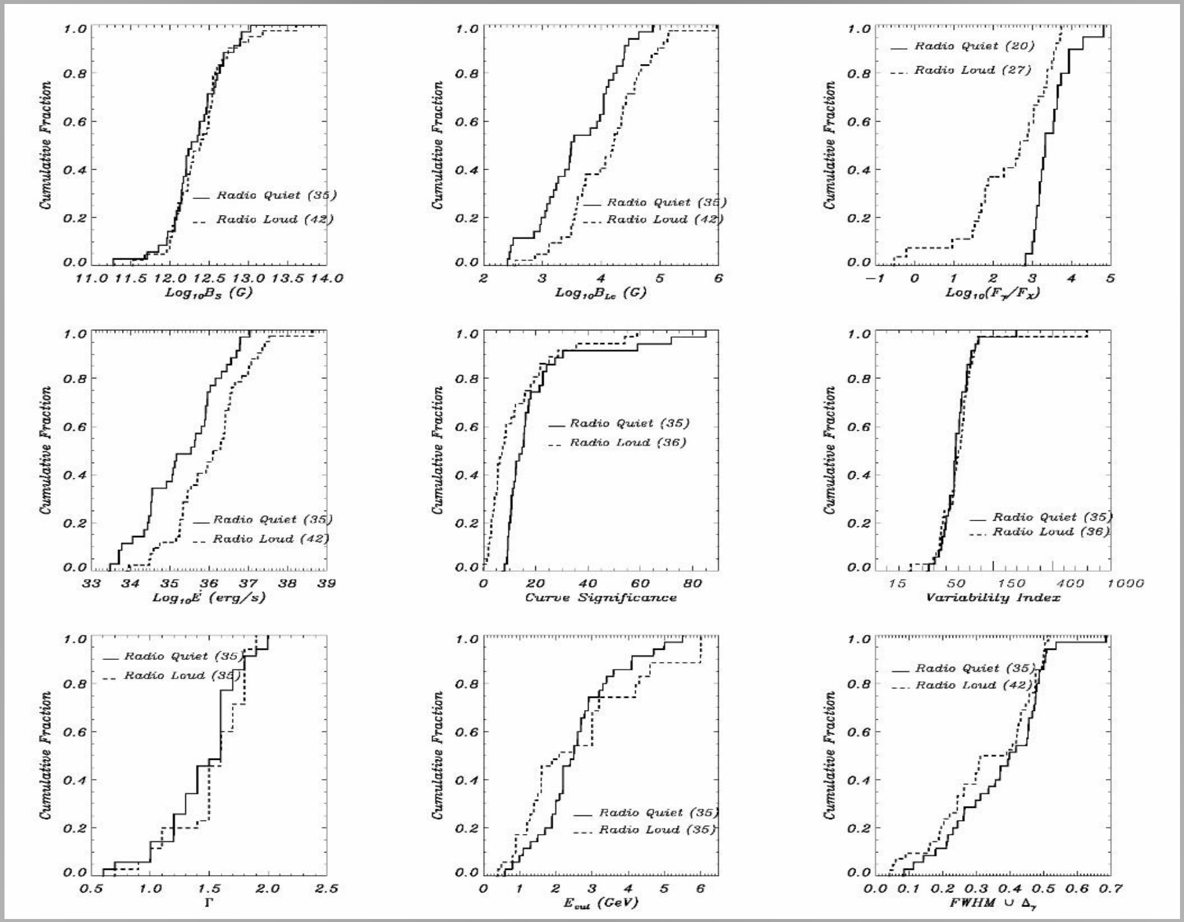
C. Sgrò[15], E. J. Siskind[70], D. A. Smith[44], F. Spada[15], G. Spandre[15], P. Spinelli[43,16],
T. E. Stephens[71], A. W. Strong[72], D. J. Suson[73], H. Takahashi[46], T. Takahashi[74],
Y. Tanaka[63], J. G. Thayer[4], J. B. Thayer[4], D. J. Thompson[45], L. Tibaldo[4], O. Tibolla[75],
D. F. Torres[59,76], E. Torresi[77], G. Tosti[29,60], E. Troja[45,62], B. Van Klaveren[4], G. Vianello[4],
B. L. Winer[78], K. S. Wood[28], M. Wood[4], S. Zimmer[32,33]

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



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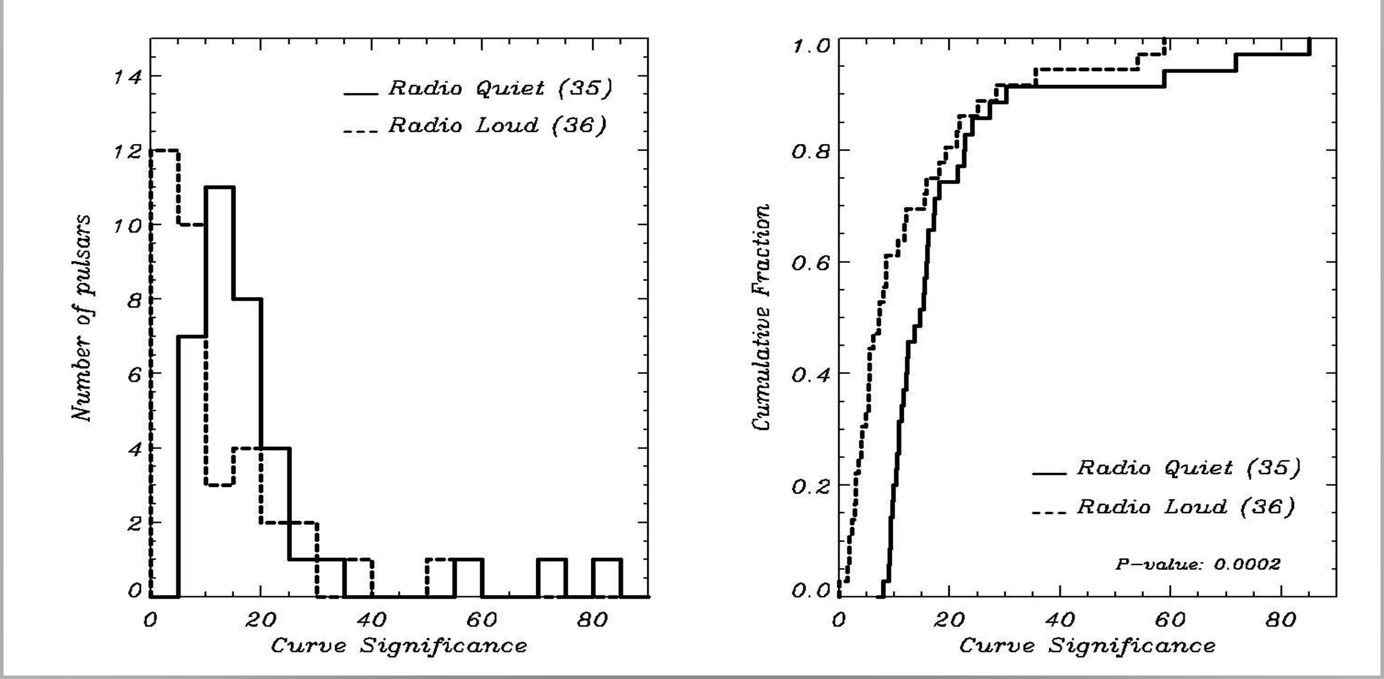
Results

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

By assuming:

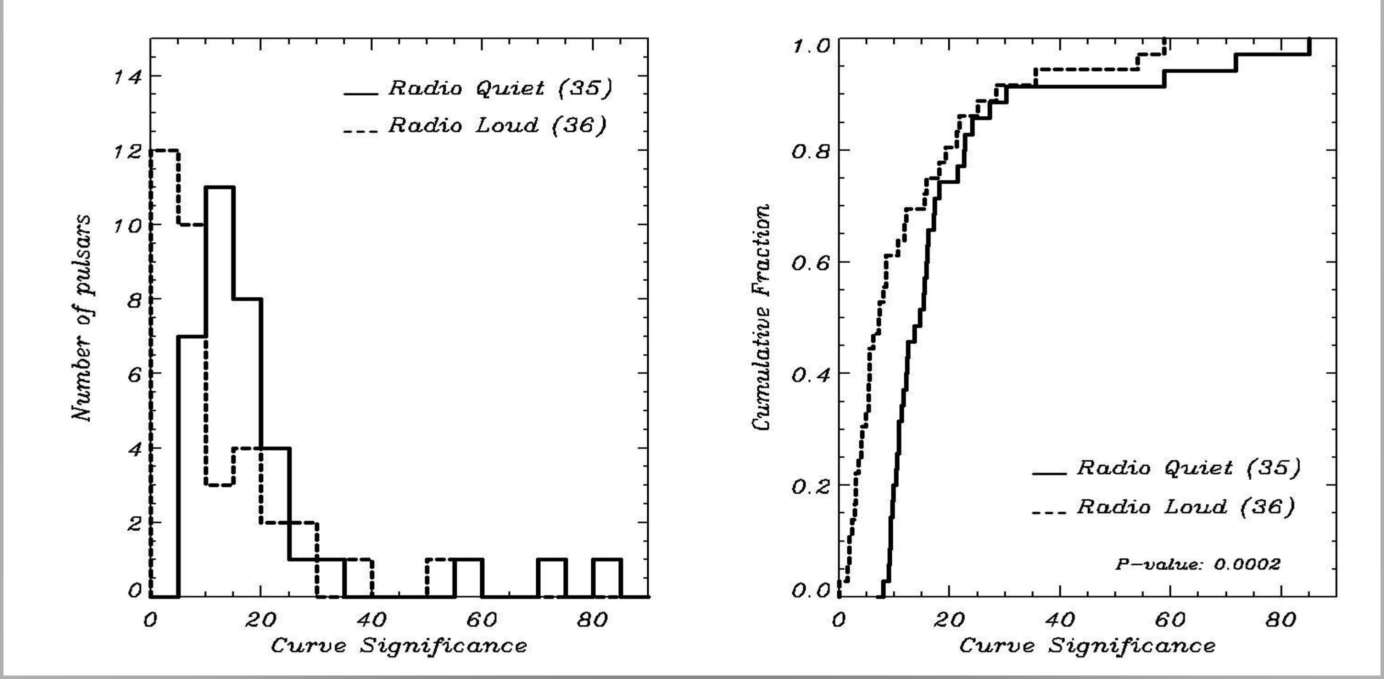
1) The gamma-ray are originated from the outer gap
2) The X-ray are originated from the polar cap due to backflow current heating
3) The open angle of the radio emission cone depends on $P^{-1/2}$

Result – Curve Significance



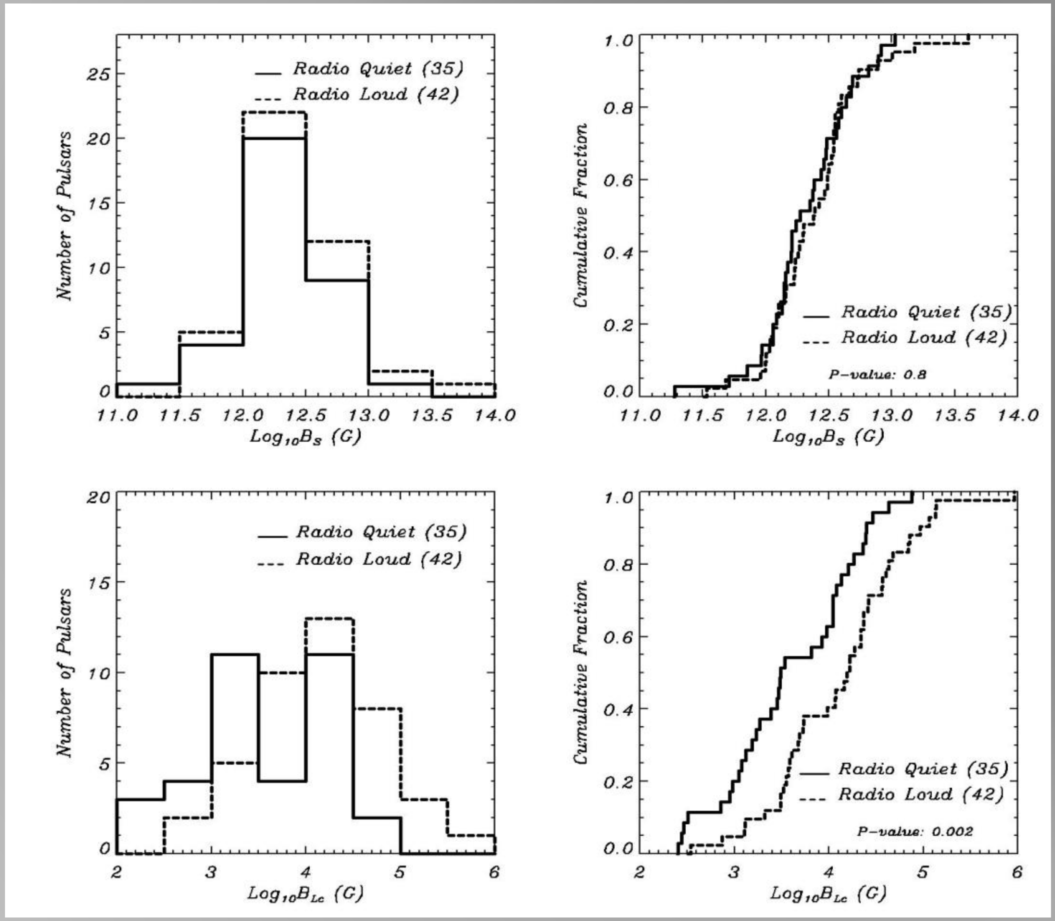
- Depends on how well the gamma-ray spectra can discriminate whether Power-Law and Power-Law with Exponential cut off.
- RL pulsars can be easily detected.
- In order to test the robustness, we alleviate this possible selection effect by re-running the AD-test on the pulsars detected at a level $> 10\sigma$ (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.

Result – Curve Significance



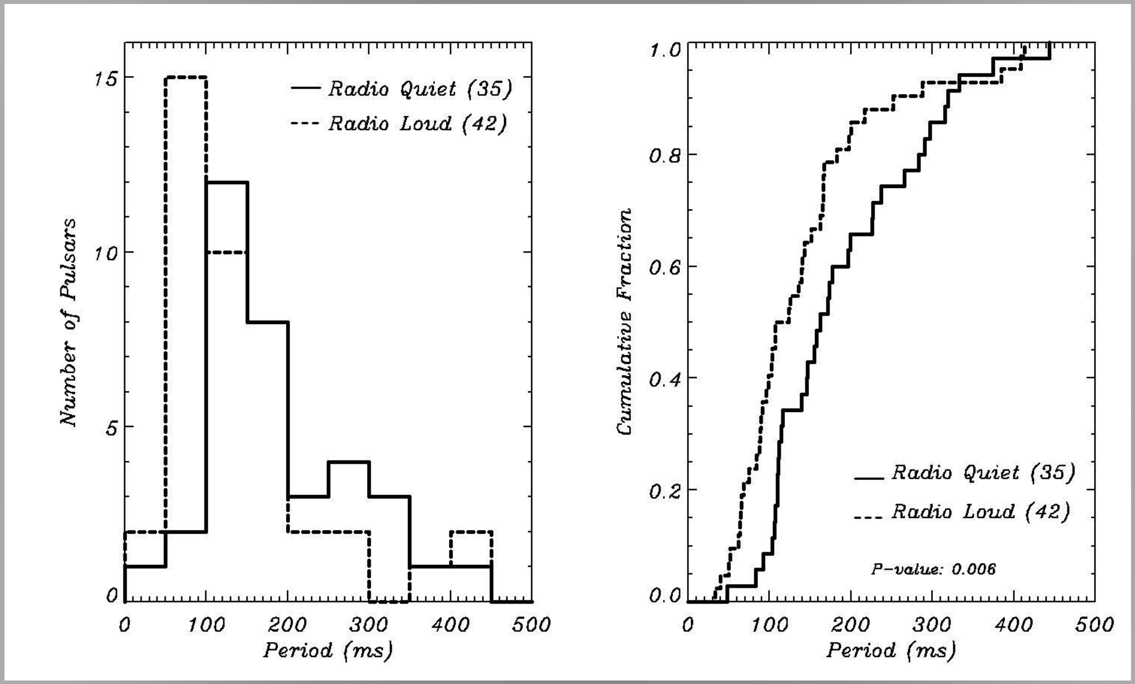
- To account for the difference of gamma-ray spectral curvature, we speculate that inverse Compton process may play a role in high energy photon production.
- RL pulsars generally have wider radio cones size.
- Part of radio emission with frequency >100 MHz may get into the outer gap and IC scatter in GeV regime.
- A shortage of photons for RQ produced at higher energies through IC process.

Result – Magnetic filed strength at stellar surface



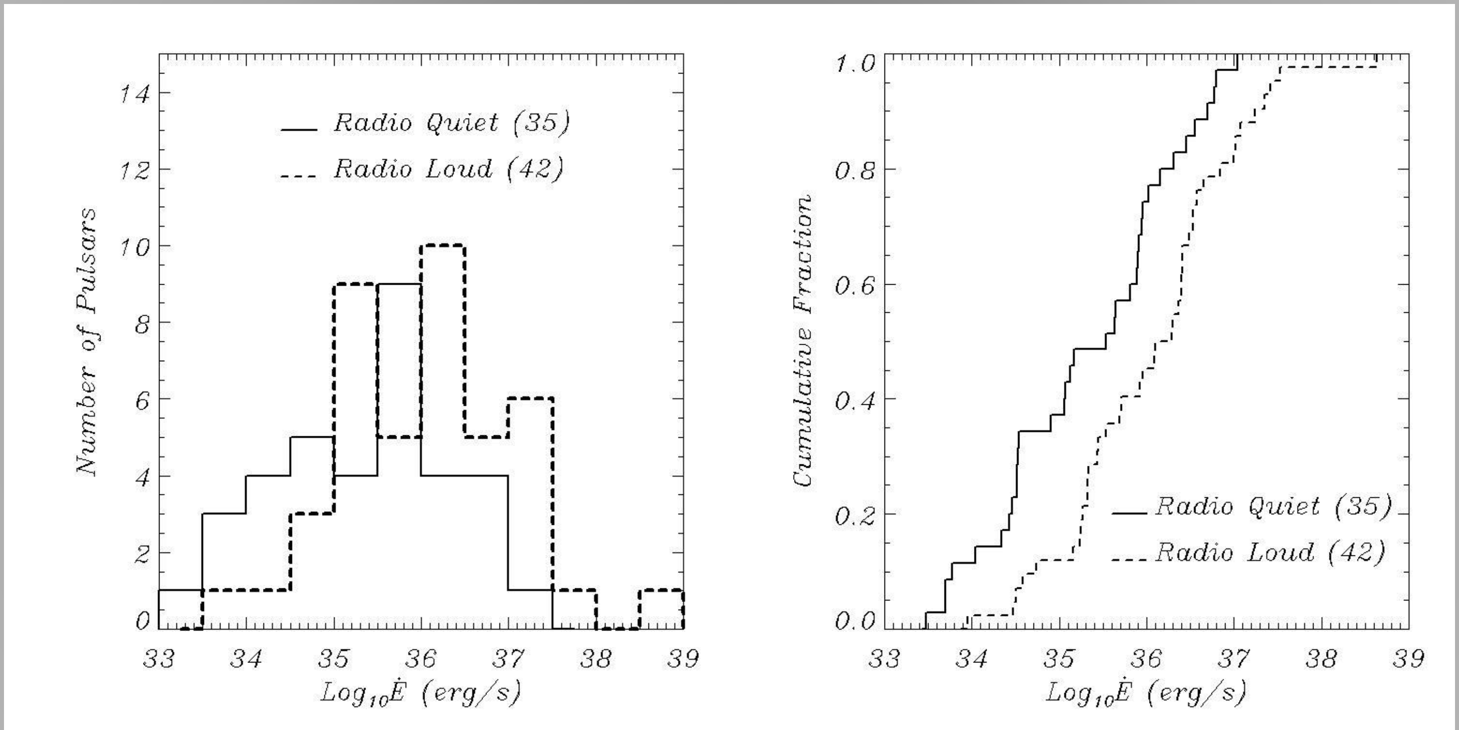
- While we do not find any difference of B_S, the distributions of the B_{LC} are found to be different.
- Both parameters are a function of P and Ṗ.
- To investigate if the B_{LC} difference is caused by their rotational parameters, we have also applied the AD test for P and Ṗ.

Result – Magnetic filed strength at light cylinder



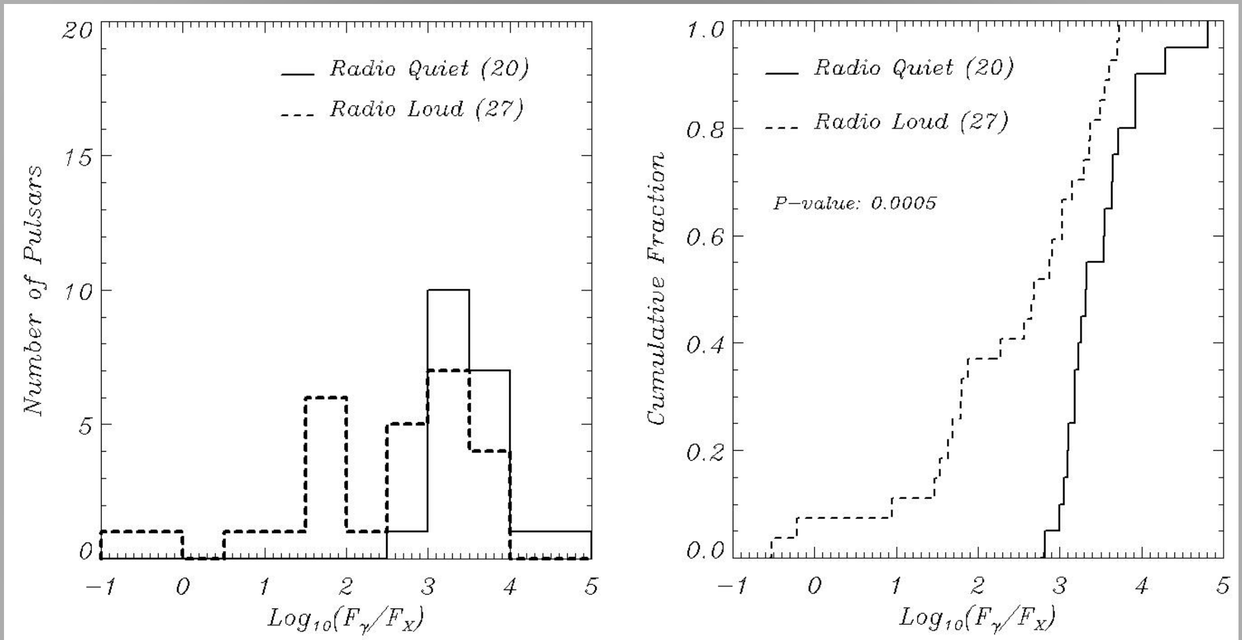
- Marginal difference of P between this two population (p-value~0.006).
- To estimate the impact of this possible selection effect in P and B_{LC}, we re-run the AD test for the pulsars detected in the blind search by Sokolova & Rubtsov.
- We found that the statistical significance for the difference in P is not undermined.
- For B_{LC} , we found the statistical signifiucance 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 $\dot{E} \sim \dot{P} P^{-3}$, Ė is influenced by period.

Result – X-ray to Gamma-ray flux ratio



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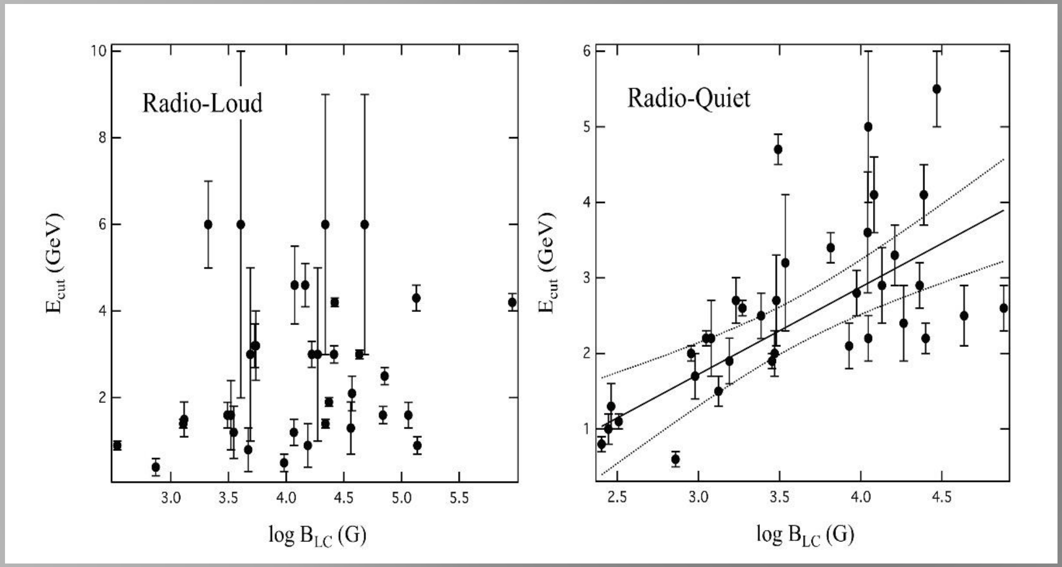
- Assumption that the X-rays are coming from the regions near the polar cap.
- $F_X^{PC} \propto cos\theta$, where θ is angle between the magnetic axis and the viewing angle .
- RL pulsars should have smaller θ than those RQ pulsars.
- From observations and simulations (e.g. Takata, Wang and Cheng 2011), the difference in the gamma-ray flux distributions between RL and RQ pulsars is not enough large.

Results for correlation



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Radio-quiet Pulsar population	
E_{cut} $VS.B_{LC}$	2.186×10^{-6}
Radio-loud Pulsar population	
E_{cut} $VS.B_{LC}$	0.1451

$$E_{cut} = (-1.74 \pm 0.36) \\ +(1.15 \pm 0.11) logB_{LC}$$

- The aforementioned IC scenario can also provide a possible way to account for this phenomena.
- E_{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.

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_γ / F_X of RQ population should be larger than the RL population.
- While we did not find correlation between E_{cut} and B_{LC} for RL population, we found strong positive correlation between E_{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 method can be adopted for the other populations.

Future work

SCIENCE ADVANCES | RESEARCH ARTICLE

ASTRONOMY

Einstein@Home discovers a radio-quiet gamma-ray millisecond pulsar

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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.

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Q & A