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Blind search for radio-quiet and radio-loud gamma-ray pulsars with Fermi-LAT data

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The Fermi Large Area Telescope (LAT) has observed more than a hundred of gamma-ray pulsars, about one third of which are radio-quiet, i.e. not detected at radio frequencies. The most of radio-loud pulsars are detected by Fermi LAT by using the radio timing models, while the radio-quiet ones are discovered in a blind search. The difference in the techniques introduces an observational selection bias and, consequently, the direct comparison of populations is complicated. In order to produce an unbiased sample, we perform a blind search of gamma-ray pulsations using Fermi-LAT data alone. No radio data or observations at optical or X-ray frequencies are involved in the search process. We produce a gamma-ray selected catalog of 25 non-recycled gamma-ray pulsars found in a blind search, including 16 radio-quiet and 9 radio-loud pulsars. This results in the direct measurement of the fraction of radio-quiet pulsars $\varepsilon_{\rm RQ} = 64 \pm 10\,\%$, which is in agreement with the existing estimates from the population modeling in the outer magnetosphere model. The Polar cap models are disfavored due to a lower expected fraction and the prediction of age dependence. The age, gamma-ray energy flux, spin-down luminosity and sky location distributions of the radio-loud and radio-quiet pulsars from the catalog do not demonstrate any statistically significant difference. The results indicate that the radio-quiet and radio-loud pulsars belong to one and the same population. The catalog shows no evidence for the radio beam evolution.

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1. Introduction. A new stage of the history of radio-quiet gamma-ray pulsars discovery began with the launch of Fermi satellite on June 11, 2008. Prior to that, the Geminga pulsar [1] stayed, for a long time, as the only identified gamma-ray pulsar without a detectable radio counterpart. The Fermi Large Area Telescopy (LAT) data enabled to discover 34 more gamma-ray pulsars with both time-differencing technique [2, 3] and a novel semi-coherent method [4, 5]. At present, 77 non-recycled pulsars are identified by Fermi LAT, 42 of which are radio-loud, see [6, 7] for review.

There are two general classes of gamma-ray pulsar models, namely the Polar cap (PC) and the outer magnetosphere (OM) models. The classes are characterized by a location of the origin of high-energy emission. In the PC model [8] the gamma rays are produced by electrons accelerated in the polar cap region near the surface of the neutron star. In the second class of models, electrons are accelerated in outer regions of the pulsar magnetosphere [9] (see also [10] for recent magnetosphere modeling results). A description of radio-quiet pulsars is different in two model classes. In PC models, gamma-ray and radio beams are produced in the same region and co-directed. In these models, pulsars are observed as radio-quiet only if existing radio survey sensitivity is not sufficient to detect radio emission [11, 12]. In the OM gamma-ray and radio beams naturally possess different geometry, which leads to a geometrical explanation of radio-quietness [13].

There is still an open question whether both radio-quiet and radio-loud pulsars belong to the same population of astronomical objects. It was noted that radio-quiet fraction is lower for young pulsars [14]. This observation may be interpreted as the time evolution of the width of the radio beam [14]. Still the selection effects may be important as the radio-quiet pulsars are identified with a completely different procedure than radio-loud. In order to exclude this possible bias in population studies, we build here the gamma-ray selected catalog of pulsars applying the same blind search procedure to all Fermi-LAT point sources, independently on the information known from radio or optical observation.

The paper is organized as follows. In Section 2, the Fermi LAT data analysis is explained. The photon list is build for each of the Fermi-LAT point sources. In Section 3, we overview the search method used for the blind

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search of pulsations. Further we estimate the threshold for the value of H-test in order to exclude a single false detection with a probability of at least 90 %. The gamma-ray selected pulsar catalog and the discussion of the results are presented in Section 4.

2. Data. We use the Fermi LAT Pass 7 (V6) publicly available weekly all-sky data for the period from 2008 August 4 to 2013 March 6, corresponding to the mission elapsed time (MET) from 239557418 to 384261063 s [15, 16]. We select SOURCE class events with energies from 100 MeV to 300 GeV and apply the standard quality cuts using *Fermi Science Tools v9r27p1*. We require that zenith angle and satellite rocking angle do not exceed 100° and 52° correspondingly.

We use all 1861 point sources from the Fermi LAT Second Source Catalog (2FGL) [17] as the candidates for the search. No preselection of the sources based on the known type and properties is performed. We use coordinates of the sources from 2FGL, although for many sources the position is known better from other observations. This is a price we pay for the blindness of the search to all data, except gamma-ray radiation. We note, however, that the efficiency of the pulsar search grows substantially if one includes the scan over the sky location [4]. The position variation requires more computational resources and therefore the search in this paper is limited to fixed positions.

For each source we build a source model which includes 2FGL sources in a 8° radius circle, galactic and isotropic diffuse emission components (version P7V6). We fit Fermi LAT events in a circle of 8° with a model by *gtlike* tool using unbinned likelihood analysis. The probability for each photon to be originated from the source under consideration is obtained by *gtsrcprob* tool. This probability is used in the following analysis as a weight of the event. For each source we keep 12000 events with the highest weights. The barycentric corrections to photon arrival times are applied with *gtbary* tool.

3. Method. The search for pulsations is performed by summing up the spectral power over sub-intervals of time range. We scan over pulsar frequency f and spin-down rate $\dot{f}$ using the set of photon barycentric arrival times t_a and corresponding weights w_a. The observation time range is split into $M = 277$ intervals of length $T = 2^{19}$ s, where the last interval is padded with zero flux up to the length T. First, the arrival times, measured in MET seconds, are corrected with

$$\tilde{t} = t + \frac{\gamma}{2}(t - t_0)^2, \qquad (1)$$

where $\gamma = \dot{f}/f$ and $t_0 = 286416002$ s (MJD 55225) is a reference epoch. We further bin each time interval into $N = 2^{25}$ bins and define $w_j^{(m)}$ as the sum of photon weights in the j-th bin for the m-th time interval. Then, the spectrum $F_j^{(m)}$ in the m-th interval is obtained with a discrete Fourier transform

$$F_k^{(m)} = \sum_j w_j^{(m)} e^{2\pi i f_k \tilde{t}_j}, \qquad (2)$$

where $f_k = k/T$ and the Nyquist frequency is $N/2T = 32$ Hz. The Fourier transform is performed with the open-source Fast Fourier transform library *fftw* [18, 19]. Finally, the statistic P_k is defined as a sum of squares of Fourier densities over M time intervals

$$P_k = \sum_{m=1}^{M} \left| F_k^{(m)} \right|^2. \qquad (3)$$

We scan over the parameter γ from 0 to $-1 \cdot 10^{-12}$ with a step equal to $-2 \cdot 10^{-15}$. The range corresponds to the pulsar characteristic age greater than 16 kyr. The values of f and $\dot{f}$ corresponding to the highest P_k are then fine-adjusted by finding a local maximum of the weighted H-test statistic [20]. The latter is defined coherently on the whole time-interval as follows:

$$H = \max_{1 \le L \le 20} \left[\sum_{l=1}^{L} |\alpha_l|^2 - 4(L-1) \right], \qquad (4)$$

where α_l is a Fourier amplitude of the l-th harmonic,

$$\alpha_l = \frac{1}{\varkappa} \sum_a w_a \exp^{-2\pi i l f \tilde{t}_a},$$
$$\varkappa^2 = \frac{1}{2} \sum_a w_a^2.$$

We define the detection threshold H_{th} in such a way that the probability to have a single false candidate in the whole set does not exceed 10 %. As the distribution of H-test statistic for non-pulsating objects is not known a priori, we construct an estimate for the particular procedure of our scan. We produce a distribution of H-test for 806 2FGL sources identified as blazars, see Fig. 1. The tail of the distribution is approximated with an exponential function and then the value $H_{th} = 83$ follows from the requirement that the integral of extrapolated distribution above H_{th} is equal to 0.1. The above background estimation technique is based on the complete scan procedure and therefore naturally accounts for data-selection and scans. Note that the threshold determination required us to involve the sources identification information, but this does not impact detection uniformity as H_{th} is a constant for all sources in the search.

Table 1

A catalog of gamma-ray pulsars found in a blind search*)

Blind search results						Information from the literature					
#	2FGL name	H-test	f, Hz	$\dot{f}$, -10^{-13} Hz s^{-1}	age, kyr	Pulsar name	l, deg	b, deg	G, 10^{-11} erg cm^{-2} s^{-1}	Type	Ref.
1	J0357.8+3205	2012	2.25172069	0.6645	537	PSR J0357+32	162.76	−16.01	6.5	Q	[2]
2	J0633.7+0633	363	3.36242020	9.0032	59	PSR J0633+0632	205.09	−0.93	9.2	Q	[2]
3	J0633.9+1746	3383	4.21755989	1.9515	343	Geminga	195.13	4.27	431.5	Q	[1]
4	J0659.7+1417	118	2.59778597	3.7182	111	Monogem pulsar	201.11	8.26	2.5	L	[22]
5	J1028.5-5819	219	10.94042233	19.2759	90	PSR J1028-5819	285.07	−0.46	24.5	L	[23]
6	J1044.5-5737	222	7.19264579	28.2455	40	PSR J1044-5737	286.57	1.16	14.9	Q	[3]
7	J1048.2-5831	145	8.08368229	62.7803	20	PSR B1046-58	287.42	0.58	20.5	L	[24]
8	J1057.9-5226	7583	5.07321954	1.5032	535	PSR B1055-52	285.98	6.65	29.3	L	[24]
9	J1413.4-6204	149	9.11230488	22.9739	63	PSR J1413-6205	312.37	-0.74	16.4	Q	[3]
10	J1459.4-6054	139	9.69449976	23.7438	65	PSR J1459-60	317.89	−1.79	12.2	Q	[2]
11	J1709.7-4429	2506	9.75607888	88.5384	17	PSR B1706-44	343.11	−2.68	135.1	L	[25]
12	J1732.5-3131	622	5.08792280	7.2595	111	PSR J1732-31	356.31	1.01	21.2	Q	[2]
13	J1741.9-2054	1269	2.41720730	0.9930	386	PSR J1741-2054	6.43	4.91	12.2	L	[2]
14	J1809.8-2332	936	6.81248059	15.9719	68	PSR J1809-2332	7.37	-2.01	49.3	Q	[2]
15	J1836.2+5926	181	5.77154958	0.5004	1828	PSR J1836+5925	88.88	25.00	60.3	Q	[2]
16	J1846.4+0920	149	4.43357097	1.9517	360	PSR J1846+0919	40.69	5.34	3.0	Q	[3]
17	J1907.9+0602	133	9.37779092	76.3568	19	PSR J1907+06	40.18	−0.89	28.2	Q	[2]
18	J1957.9+5033	149	2.66804365	0.5040	839	PSR J1957+5033	84.58	11.01	2.8	Q	[3]
19	J1958.6+2845	408	3.44356138	25.1308	22	PSR J1958+2846	65.88	-0.35	9.5	Q	[2]
20	J2021.0+3651	496	9.63902060	89.1185	17	PSR J2021+3651	75.23	0.12	48.9	L	[26]
21	J2028.3+3332	93	5.65907215	1.5721	571	PSR J2028+3332	73.36	−3.01	6.1	Q	[4]
22	J2030.0+3640	118	4.99678975	1.6230	488	PSR J2030+3641	76.12	-1.44	3.7	L	[27]
23	J2032.2+4126	103	6.98089418	10.1823	109	PSR J2032+4127	80.22	1.03	14.4	L	[2]
24	J2055.8+2539	513	3.12928982	0.4005	1238	PSR J2055+25	70.69	−12.52	5.6	Q	[3]
25	J2238.4+5902	96	6.14486827	36.6124	27	PSR J2238+5903	106.56	0.48	6.3	Q	[2]

*) Frequency f and spin-down rate $\dot{f}$ of gamma-ray pulsations correspond to the epoch MJD 55225. Age is estimated as $-f/2\dot{f}$. The last six columns contain the object information from the literature: pulsar name, galactic coordinates, Fermi LAT energy flux for $E > 100$ MeV [17], type (Q – radio-quiet, L – radio-loud) and a reference to the first identification of gamma-ray pulsations. The improved pulsar positions from [21] are shown for the objects they are available.

4. Results. We apply the procedure of Section 3 to all 1861 point sources of the 2FGL catalog. As a result, 25 objects are found with the value of H-test above the threshold H_{th}, see Table 1. It appears that all of the pulsation detections correspond to known gamma-ray pulsars, 16 of which are radio-quiet and 9 are radio-loud, see last six columns of Table 1. This allows us to estimate directly the fraction of radio-quiet pulsars

$$\varepsilon_{\mathrm{RQ}} \equiv \frac{N_{\mathrm{RQ}}}{N_{\mathrm{RQ}} + N_{\mathrm{RL}}} = 0.64 \pm 0.10 \text{ (68\% CL)}, \qquad (5)$$

where N_{RQ} and N_{RL} are numbers of radio-quiet and radio-loud non-recycled gamma-ray pulsars. It should be mentioned that the radio-quietness is determined according to the present-day sensitivity of radio surveys. It is possible that faint radio emission will be detected in the future from some of todays radio-quiet pulsars.

The fraction above confirms the domination of radio-quiet pulsars and is perfectly consistent with the predictions of population synthesis with OM model which gives a value of 0.65 [13]. The PC model with inverse Compton gamma-ray production estimates the fraction as 0.25 [11] which is excluded by the observation. A curvature radiation version of the PC model leads to the fraction value of 0.49–0.53 [12] which is slightly disfavored. Moreover, the model [12] is further disfavored due to its prediction of the decrease of radio-quiet fraction with age. Considering pulsars older than 100 kyr the model expectation of radio-quiet fraction 0.36 should be compared with 0.62 ± 0.13 in our catalog.

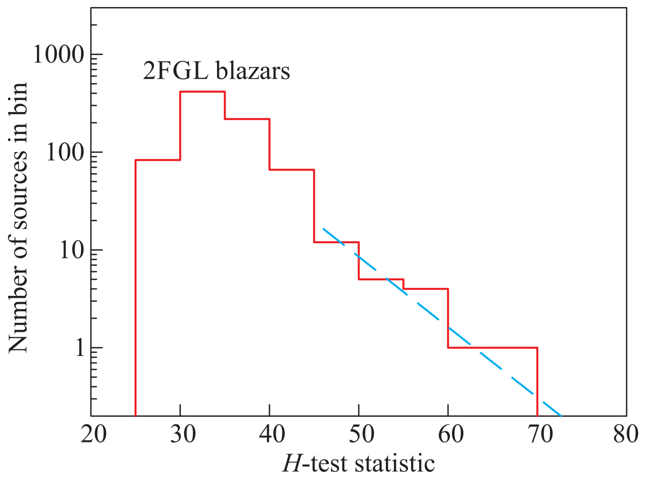

Fig. 1. The distribution of H-test statistic for 2FGL identified blazars. Dashed line represents an exponential fit of the tail

The P–$\dot{P}$ plot for the pulsars from our catalog is shown in Fig. 2. The distributions of characteristic age

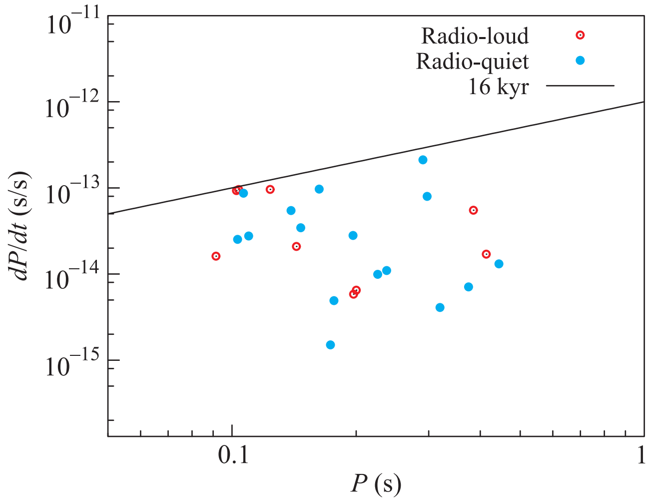

Fig. 2. P–$\dot{P}$ plot for 25 pulsars found with a blind search in the present Paper. $P = 1/f$ is a rotation period. The search is limited to characteristic ages $\tau_c > 16$ kyr which correspond to the area below the solid line

for radio-loud and radio-quiet pulsars are compatible with the Kolmogorov–Smirnov (KS) probability 54 %, see Fig. 3. Therefore there is no indication for the radio beam evolution. We note, hovewer, that the pulsars younger that $\sim$16 kyrs are outside of the search range of the present Paper.

The comparison of distributions over galactic coordinates, gamma-ray energy flux and spin-down luminosity indicate that both radio-loud and radio-quiet pulsars belong to the same population, see Table 2. The agreement

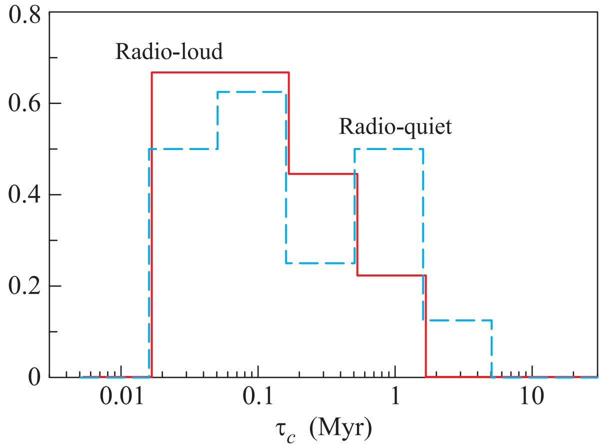

Fig. 3. Distributions of characteristic age $\tau_c = -f/2\dot{f}$ for radio-loud and radio-quiet pulsars. The two distrubutions are compatible with KS probability 54 %

Table 2

The KS-test probabilities for comparison of radio-quiet and radio-loud pulsar distributions over age, spin-down luminosity, energy flux above 100 MeV and galactic coordinates

Parameter	KS probability, %
Age ($-f/2\dot{f}$)	54
Luminosity ($\sim f\dot{f}$)	72
Gamma energy flux	43
l	75
b	69

of the parameter distributions is an additional argument in favor of the geometrical origin of radio-quietness and therefore OM pulsar models are preferable. On the contrary, the PC models unavoidably result in a strong age dependence of the fraction of radio-quiet pulsars.

Given that Fermi LAT has by now observed 42 nonrecycled radio-loud pulsars, we expect according to our value of $\varepsilon_{\mathrm{RQ}}$ that there are about 75 radio-quiet pulsars among the Fermi-LAT sources. The pulsed emission is discovered for only 35 of them leaving $\sim$40 sources as a challenge for the future pulsation searches. In accord with our result, the machine-learning classification of Fermi-LAT unidentified sources points to more than 50 gamma-pulsar candidates [28].

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