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On the Spectral Shape of Non-recycled γ-ray Pulsars

Chung-Yue Hui[†], **Jongsu Lee**
Department of Astronomy, Space Sciences and Geology, Chungnam National University, Daejeon 34134, Korea

More than 100 γ–ray pulsars have been discovered by the *Fermi* Gamma-ray Space Telescope. With a significantly enlarged sample size, it is possible to compare the properties of different classes. Radio-quiet (RQ) γ–ray pulsars form a distinct population, and various studies have shown that the properties of the RQ population can be intrinsically different from those of radio-loud (RL) pulsars. Utilizing these differences, it is possible to further classify the pulsar-like unidentified γ–ray sources into sub-groups. In this study, we suggest the possibility of distinguishing RQ/RL pulsars by their spectral shape. We compute the probabilities of a pulsar to be RQ or RL for a given spectral curvature. This can provide a key to the estimation of the intrinsic fraction of radio-quietness in the γ–ray pulsar population, which can place a tight constraint on the emission geometry.

Keywords: gamma rays: stars - pulsars: genera

1. INTRODUCTION

Together with an improved pulsation search algorithm (e.g., Kerr 2011), the large area telescope (LAT) onboard *Fermi* γ-ray Space Telescope has significantly enlarged the population of γ-ray pulsars with its unprecedented sensitivity. In the second *Fermi* LAT pulsar catalog (2PC Abdo et al. 2013), 117 pulsar detections at energies > 100 MeV are reported using three years of data. It comprises 42 radio-loud (RL) pulsars, 35 radio-quiet (RQ) pulsars and 40 millisecond pulsars (Abdo et al. 2013)[1]. It should be noted that the fractions of RL and RQ are comparable in the known γ–ray pulsar population. However, the true RL/RQ fractions can be different from the observed values in the presence of various selection effects. For example, blind searches for RQ pulsars can only be performed in high energy regimes, which are photon-limited. On the other hand, in the case of searching RL γ-ray pulsars, one can utilize the ephemeris obtained in radio. This implies that the intrinsic RQ fraction can be larger than the observed one by ~30%. In a recent study, Sokolova & Rubtsov (2016) estimated that the intrinsic fraction of radio-quiet γ–ray pulsars can be as large as ~70%.

Knowing the true fraction of RQ is important for constraining the pulsar emission models. The outer-gap model suggests that γ–rays originate from the outer magnetosphere and form a fan beam (see Cheng & Zhang 1998; Takata et al. 2006, 2008). On the other hand, the radio emission forms a narrow cone when it originates from the polar cap region (Kijak & Gil 1998, 2003). The ratio of RL and RQ populations can help us to constrain the emission and viewing geometry. As RL and RQ pulsars form two distinct populations, a number of investigations have compared the properties of these two classes. Marelli et al. (2011, 2015) and Marelli (2012) found the difference between these two populations in terms of the γ–ray-to-X-ray flux ratio F_γ/F_X. F_γ/F_X of the RQ population was found to be significantly higher than that of the RL population. Sokolova & Rubtsov (2016) also reported a possible difference in the distributions of their rotation periods. Very recently, Hui et al. (2016) examined the various physical properties of RQ and RL γ–ray pulsars. Among all the possible differences found in these two populations, the most significant is the curvatures of their γ–ray spectra.

Using various different properties identified for RQ and

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[1] Radio-loud or radio-quiet in 2PC is based on its radio flux density at 1.4 GHz whether it is larger or smaller than 30 μJy.

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[†]**Corresponding Author**
E-mail: cyhui@cnu.ac.kr , ORCID: 0000-0003-1753-1660
Tel: +82-42-821-7491, Fax: +82-42-824-8891

RL pulsars, we suggest a method to estimate the intrinsic fraction of radio-quietness in the population of γ–ray pulsars. In the third *Fermi* γ–ray point sources catalog (3FGL; Acero et al. 2015), among 3,033 sources detected at a significance > 4σ, more than 1,000 sources do not have any known counterparts at other energy bands. Using the γ–ray properties of pulsars (e.g., variability, curvature significance, locations in our galaxy) together with the machine learning techniques, Saz Parkinson et al. (2016) selected a group of pulsar-like unidentified γ–ray sources and further classified them into the categories of young pulsars and millisecond pulsars. Applying the same techniques together with the aforementioned features that can distinguish the RQ and RL pulsars, it is feasible to select the non-recycled pulsar candidates from the unidentified source population and classify them into RQ or RL classes. This can provide a less biased estimate for the radio-quietness fraction. In this paper, we discuss the possibility of using the γ–ray spectral shape to distinguish RQ and RL pulsars.

2. DATA ANALYSIS

The γ–ray spectra of pulsars are characterized by the form of a power-law with an exponential cut-off (PLE),

$$\frac{dN}{dE} = N_0 E^{-\Gamma} exp(-\frac{E}{E_c}) \qquad (1)$$

where N_0, Γ, and E_C are the normalization, photon index, and cut-off energy, respectively. This is significantly curved in comparison with a simple power-law (PL):

$$\frac{dN}{dE} = N_0 E^{-\Gamma} \qquad (2)$$

In the 3FGL catalog, the curvature of the pulsars' γ–ray spectra is quantified by the parameter Curve Significance, which is obtained by comparing the difference between the PLE and PL model fittings in unit of σ. Using the K-S test, Hui et al. (2016) found that the distributions of Curve Significance show the most significant difference between RQ and RL pulsars among all the tested parameters. The difference is found at a confidence level of > 99.999%. In Table 1, we have tabulated the Curve Significance for all the non-recycled RQ and RL pulsars in 2PC. All the data in this table are collected from 3FGL (Acero et al. 2015). Hui et al. (2016) showed histograms of Curve Significance for both populations. Using these distributions, we can compute the posterior probabilities of being RQ (P(RQ|Cur)) or RL (P(RL|Cur)) for a given Curve Significance.

In examining the distributions reported by Hui et al. (2016), we notice the fluctuations appear at the large values of Curve Significance. This can be ascribed to the small statistics in this range. For a simple parametric estimation of the underlying probability density function, we suppress these noises by fitting the histograms with Gaussian models with the following form:

$$P(x) = Aexp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] \qquad (3)$$

where A, μ, and σ are the parameters that depict the peak, the mean, and the width of the model, respectively. For the RQ population, all three parameters, A, μ, and σ, are set to be free in the fitting. For the RL population, visual inspection clearly indicates that the peak and the mean are located

Table 1. Curvature Significances of RL γ-ray pulsar (Acero et al. 2015)

Radio − quiet PSR	Curvature Significance	*Radio − loud* PSR	Curvature Significance
J0007+7303	22.7	J0205+6449	4.9
J0106+4855	9.3	J0248+6021	7.1
J0357+3205	22.7	J0534+2200	15.8
J0622+3749	9.7	J0631+1036	8.0
J0633+0632	17.3	J0659+1414	7.3
J0633+1746	85.0	J0729-1448	1.4
J0734-1559	10.2	J0742-2822	4.1
J1023-5746	15.3	J0835-4510	54.0
J1044-5737	15.7	J0908-4913	1.9
J1135-6055	9.0	J0940-5428	···
J1413-6205	16.0	J1016-5857	5.5
J1418-6058	16.1	J1019-5749	3.1
J1429-5911	14.6	J1028-5819	21.3
J1459-6053	11.3	J1048-5832	18.1
J1620-4927	12.2	J1057-5226	58.7
J1732-3131	27.3	J1105-6107	1.8
J1746-3239	9.3	J1112-6103	5.2
J1803-2149	9.1	J1119-6127	2.3
J1809-2332	30.2	J1124-5916	8.5
J1813-1246	17.2	J1357-6429	2.9
J1826-1256	24.0	J1410-6132	2.8
J1836+5925	71.8	J1420-6048	4.0
J1838-0537	9.6	J1509-5850	10.6
J1846+0919	10.7	J1513-5908	0
J1907+0602	18.1	J1531-5610	···
J1954+2836	13.6	J1648-4611	6.2
J1957+5033	10.8	J1702-4128	···
J1958+2846	15.4	J1709-4429	28.5
J2021+4026	58.8	J1718-3825	8.5
J2028+3332	12.3	J1730-3350	···
J2030+4415	11.7	J1741-2054	25.1
J2055+2539	21.4	J1747-2958	11.8
J2111+4606	8.0	J1801-2451	···
J2139+4716	10.5	J1833-1034	3.5
J2238+5903	12.5	J1835-1106	···
		J1952+3252	19.3
		J2021+3651	35.5
		J2030+3641	12.1
		J2032+4127	15.5
		J2043+2740	5.5
		J2229+6114	21.7
		J2240+5832	5.3

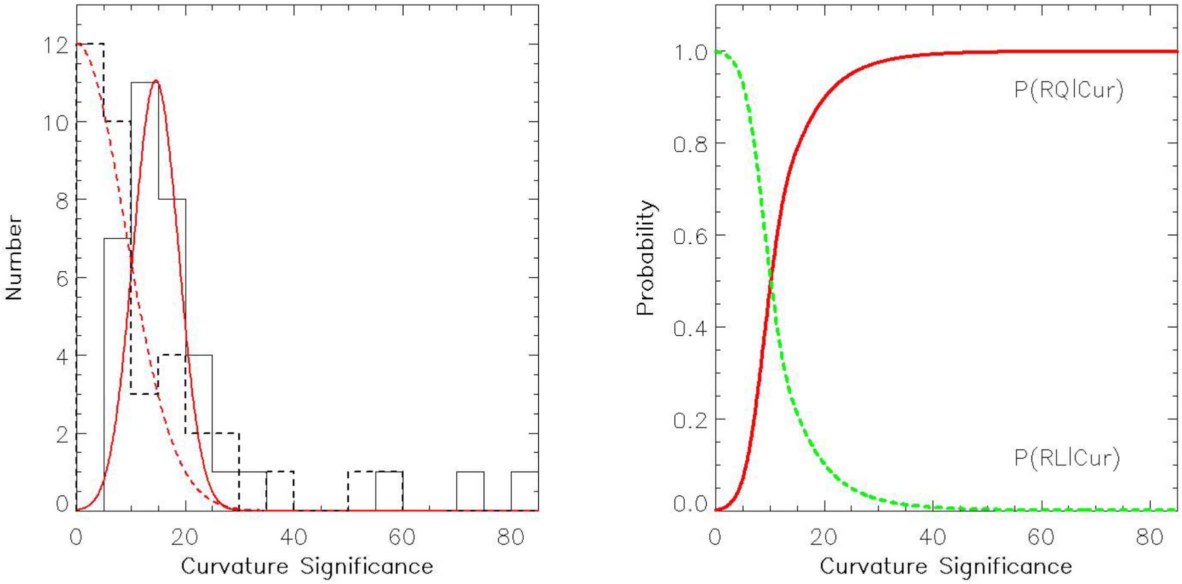

Fig. 1. (Left panel) Distributions of Curve Significance for RL (dashed lines) and RQ (solid lines) γ–ray pulsars in 2PC. The best-fit Gaussian functions of both populations are overlaid (right panel). The probabilities of a non-recycled γ–ray pulsar to be RL P(RL|Cur) or RQ P(RQ|Cur) for a given Curve Significance are computed from the best-fit Gaussians.

around zero Curve Significance. Therefore, A and μ are fixed and we only let the width of the function σ be free. The best-fit functions are shown in the left panel of Fig. 1, which provides a reasonable approximation of the distributions. Using these estimates of probability density functions, we further construct the posterior probabilities P(RQ|Cur) and P(RL|Cur) and have shown them in the right panel of Fig. 1.

3. DISCUSSIONS

As γ–ray spectral curvatures of non-recycled RQ and RL pulsars in 2PC are found to be significantly different (Hui et al. 2016), one can use this aspect as an additional feature in classifying those sources that have no known multi-wavelength counterparts. To facilitate the classification, we have computed P(RQ|Cur) and P(RL|Cur), which can help to estimate the probability of any non-recycled pulsar-like candidate being RQ or RL by giving its Curve Significance.

We strongly believe such investigation as this can provide a less biased estimate of the intrinsic fraction of radio-quietness. By performing a blind pulsation search for all point sources in 3FGL with *Fermi* LAT data alone, Sokolva & Rubtsov (2016) estimated the radio-quietness fraction to be $\epsilon_{RQ} = 63 \pm 8\%$. The catalog they compiled is free from the bias as RL pulsar search can utilize the information through radio observations. However, one should note that blind search of such a large sample is computationally demanding. On the other hand, our proposed method can provide an independent estimate by using the spectral curvature. Combining the spectral feature with the method of selecting pulsar candidates (e.g. see Fig. 1 in Hui et al. 2015), one may estimate ϵ_{RQ} simply using Curve Significance, P(RQ|Cur) and P(RL|Cur) as inputs.

The aforementioned comparison of the γ–ray spectral curvature is only for the non-recycled pulsars. There is no existing literature on a similar analysis of millisecond pulsars (MSPs). It will be interesting to compare the spectral features and other γ–ray properties of MSPs with those of non-recycled RQ and RL pulsars. This kind of study can help to search for the possible features that can make the MSP candidate selection more accurate (see Hui et al. 2015). Also, to date, no MSP has been found to be RQ. Through such comparison, one may draw insights on the expected properties of RQ MSPs, if they exist.

Finally, we would like to stress that the density estimation in this work is obtained through a simple parametric estimation and limited by the relatively small sample size. With an enlarged γ–ray pulsar population in the future, our estimation can be improved by employing a more sophisticated method of density estimation (e.g., using kernels).

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