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Possible distance indicators in gamma-ray pulsars *

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Abstract Distance measurement of gamma-ray pulsars is a current challenge in pulsar studies. The Large Area Telescope (LAT) aboard the Fermi gamma-ray observatory discovered more than 70 gamma-ray pulsars including 24 new gamma-selected pulsars with almost no distance information. We study the relation between gamma-ray emission efficiency ($\eta = L_\gamma/\dot{E}$) and pulsar parameters for young radio-selected gamma-ray pulsars with known distance information in the first gamma-ray pulsar catalog reported by Fermi/LAT. We have introduced three generation-order parameters to describe the gamma-ray emission properties of pulsars, and find a strong correlation of $\eta - \zeta_3$, a generation-order parameter which reflects γ-ray photon generation in the pair cascade processes induced by magnetic field absorption in a pulsar's magnetosphere. A good correlation of $\eta - B_{\rm LC}$, the magnetic field at the light cylinder radius, is also found. These correlations are the distance indicators in gamma-ray pulsars used to evaluate distances for gamma-selected pulsars. Distances of 25 gamma-selected pulsars are estimated, which could be tested by other distance measurement methods. The physical origin of the correlations may also be interesting for pulsar studies.

Key words: gamma rays: general — pulsars: general — stars: neutron

1 INTRODUCTION

Before 2008, only seven gamma-ray pulsars were known (Thompson 2001). The launch of the Fermi Gamma-ray Space Observatory in June 2008 completely changed the status of gamma-ray pulsar studies. The first published catalog of gamma-ray pulsars (Abdo et al. 2010) contains 46 gamma-ray pulsars, including 8 millisecond pulsars, 21 young radio pulsars and 17 gamma-selected pulsars. After more than one and one-half years of all-sky survey observations by Fermi/LAT, more than 70 gamma-ray pulsars have been discovered, including 25 gamma-selected pulsars (see reviews by Ray & Saz Parkinson 2010). The high sensitivity of Fermi/LAT enables a new era for pulsar discoveries, especially for the population of radio-quiet gamma-ray pulsars.

Distance measurement in pulsar studies is always a difficult problem. Trigonometric parallax measurements of radio pulsars are a reliable method, but are only available for nearby pulsars (<0.4 kpc), including a few radio millisecond pulsars (e.g. Lommen et al. 2006). The most common way to obtain radio pulsar distance is based on computation from the dispersion measurement

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(DM) coupled to an electron density distribution model such as the NE 2001 model (Cordes & Lazio 2002), which has been applied to most radio pulsars (e.g., Johnston et al. 1996; Keith et al. 2008). The pulsar distance can also be estimated from a kinematic model: the distance to possible associated objects (supernova remnants, pulsar wind nebulae, star clusters or HII regions) can be measured from the Doppler shift of absorption or emission lines in their HI spectrum together with the rotation curve model of the Galaxy (e.g., Roberts et al. 1993; Camilo et al. 2006). The distance of some pulsars computed with X-ray emissions can be estimated from X-ray observations of the absorbing column (e.g. Romani et al. 2005) or from correlations in X-ray luminosities versus spin-down power or photon index (Becker & Truemper 1997; Possenti et al. 2002; Gotthelf 2003; Wang 2009 and references therein). These methods may be available for radio or even X-ray pulsars, but for gamma-selected pulsars, if there are no associated objects available, we do not have any information on their distance.

It is well known that X-ray luminosity has a correlation with a pulsar's spin-down power: $L_x \propto \dot{E}$ in soft X-ray bands (0.1–2.4 keV, Becker & Truemper 1997), and $L_x \propto \dot{E}^{3/2}$ in hard X-ray bands ($>$2 keV, see Saito 1998; Cheng et al. 2004; Wang 2009). Based on the EGRET pulsars, Thompson et al. (1999) found a possible correlation of $L_\gamma \propto \dot{E}^{1/2}$. For the larger sample of gamma-ray pulsars in Abdo et al. (2010), the young pulsars appear to also follow this relation with large scattering factors of more than 10, however millisecond pulsars follow a different relation (see fig. 6 of Abdo et al. 2010). This correlation was used to estimate some gamma-selected pulsars (Saz Parkinson et al. 2010). Moreover, the relation of $L_\gamma \propto \dot{E}^{1/2}$ may not be intrinsic; for the young gamma-ray pulsars in figure 6 of Abdo et al. (2010), we find a fitting function of $L_\gamma \propto \dot{E}^{0.7}$.

Gamma-ray emission efficiency ($\eta = L_\gamma/\dot{E}$) is an important parameter in gamma-ray pulsars, which varies for different populations of pulsars. In this paper, we study the relations of gamma-ray emission efficiency versus some pulsar parameters: spin period, age, magnetic field at the light cylinder and three generation-order parameters. We will show the results of these relations, and the derived good correlations can be pulsar distance indicators for gamma-selected pulsars.

2 GAMMA-RAY EMISSION EFFICIENCY VERSUS PULSAR PARAMETERS

Gamma-ray emission efficiency is defined as $\eta = L_\gamma/\dot{E}$, where the spin-down power $\dot{E} = 4\pi^2 I\dot{P}P^{-3}$ taking $I = 10^{45}$ g cm^2. P is the period of the pulsar in units of seconds. $L_\gamma = 4\pi d^2 f_\Omega F_\gamma$, where F_γ is the gamma-ray flux above 100 MeV detected by Fermi/LAT. The radiation open angle factor f_Ω is model-dependent and may depend on the magnetic inclination and observer angles, which can be obtained using pulse profile information (e.g., $f_\Omega \sim 1$ for the eight gamma-ray pulsars estimated by Watters et al. 2009). For simplicity, we use $f_\Omega = 1$ in this paper, similar to Abdo et al. (2010). In the gamma-ray pulsar catalog given by Abdo et al. (2010), 21 radio-selected young pulsars and 7 gamma-selected pulsars have distance measurements or estimations. However, the gamma-ray emission efficiency of some gamma-selected pulsars is higher than 1, the maximum radiation efficiency in physics, suggesting there is an overestimation of the distance for some gamma-selected pulsars. Millisecond pulsars may have different properties from young pulsars, so we do not consider the eight millisecond pulsars in the catalog here. Finally, we use these 21 radio-selected pulsars for the analysis in this section. The efficiency η is distributed from 0.1% (like the Crab pulsar) to nearly 100%.

We will first show the relations between η versus three well-known pulsar parameters: P, τ and $B_{\rm LC}$. Most importantly, we have introduced the generation-order parameters for pulsars (see details in Wang & Zhao 2004 and references therein), which can be used to describe gamma-ray properties in pulsars. In Section 2.2, the relations between η versus three generation-order parameters will be studied.

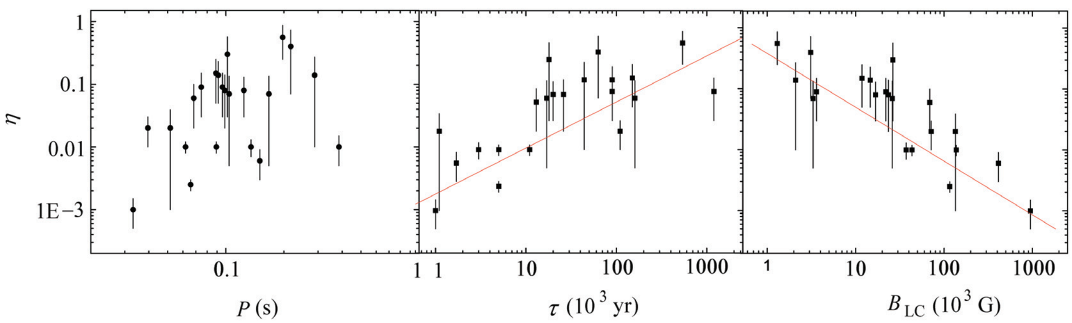

Fig. 1 Gamma-ray emission efficiency η of 21 young gamma-ray pulsars versus three pulsar parameters: spin period P, age τ and the magnetic field in the light cylinder $B_{\rm LC}$. η shows the correlations with two pulsar parameters τ and $B_{\rm LC}$, and the solid lines display the best fitting functions. See the text for details.

2.1 η versus P, τ and $B_{\rm LC}$

In Figure 1, we plot diagrams of η versus P, τ and $B_{\rm LC}$ for 21 young gamma-ray pulsars, respectively. Here $\tau = P/\dot{P}$ is the pulsar's characteristic age, and $B_{\rm LC} \sim 2.94 \times 10^8(\dot{P}P^{-5})^{1/2}$ is the magnetic field at the light cylinder ($R_{\rm LC} = cP/2\pi$).

In the diagram of $\eta - P$, the data points of the spin period are scattered and no significant correlation is found. However, η seems to have correlations with the other two pulsar parameters: age and the magnetic field at the light cylinder. A linear function is used to fit the correlations (solid lines in Fig. 1)

$$\log\eta = -(4.73 \pm 0.31) + (0.68 \pm 0.08)\log\tau \tag{1}$$

with a standard deviation of $\sigma \sim 1.63$ and a probability value (p-value for t-test) of 1.09×10^{-4},

$$\log\eta = (2.23 \pm 0.32) - (0.88 \pm 0.10)\log B_{\rm LC} \tag{2}$$

with $\sigma \sim 1.56$ and a p-value of 2.90×10^{-5}.

The gamma-ray efficiency generally becomes higher with older ages and smaller $B_{\rm LC}$. From the evaluation of the standard deviation values σ and p-values, the relation of $\eta - B_{\rm LC}$ is the better one.

2.2 η versus generation-order parameters

The concept of generation is provided to describe the pair cascade processes in gamma-ray pulsars (Zhao et al. 1989; Lu & Shi 1990). Based on the Ruderman-Sutherland scenario (Ruderman & Sutherland 1975), passing through the polar gap, $\mathrm{e}^+/\mathrm{e}^-$ are accelerated to a high energy with a typical Lorentz factor $\gamma_1 = 6.0 \times 10^7 P^{1/14}\dot{P}_{15}^{-1/14}$, where $\dot{P}_{15}$ is the derivative in units of 10^{-15}s s^{-1}. These first-generation particles will move along the curved magnetic field lines and emit high energy curvature radiation (the first-generation photons) with photon energy typically at

$$E_1 = \frac{3}{2}\frac{\hbar c}{R_c}\gamma_1^3 \approx 3.2 \times 10^{10} P^{-2/7}\dot{P}_{15}^{-3/14}\mathrm{eV}, \tag{3}$$

where $R_c \approx 1.8 \times 10^7 P^{1/2}$cm is the curvature radius of field lines here. These primary photons can be converted into secondary $\mathrm{e}^+/\mathrm{e}^-$ pairs in both open and closed magnetic field line regions near the neutron star's surface due to magnetic pair creation (Halpern & Ruderman 1993). In addition, the condition for these photons to create $\mathrm{e}^+/\mathrm{e}^-$ pairs is (Sturrock 1971; Ruderman & Sutherland 1975)

$$\frac{E_1}{2m_e c^2}\frac{B(r_\mathrm{s})}{B_c} \approx \frac{1}{15}, \tag{4}$$

where $B(r_\mathrm{s})$ is the local magnetic field at the position of r_s, and $B_c = m_\mathrm{e}^2 c^3/e\hbar = 4.14 \times 10^{13}$ G is the critical magnetic field. These $\mathrm{e}^+/\mathrm{e}^-$ can emit second-generation photons through curvature radiation with a characteristic energy E_2. If E_2 is high enough, the subsequent $\mathrm{e}^+/\mathrm{e}^-$ pairs (the third-generation) can be produced under conditions similar to Equation (4),

$$\frac{E_2}{2m_e c^2}\frac{B(r_\mathrm{s})}{B_c} \approx \frac{\chi_0}{15}, \tag{5}$$

where $\chi_0/15 \sim 1/9 - 1/12$ (Sturrock 1971). Then pair cascade processes occur.

Concerning this idea, Lu et al. (1994) introduced the generation-order parameter (GOP) to characterize a pulsar. They considered the conversion of high energy photons into $\mathrm{e}^+/\mathrm{e}^-$ pairs through electric fields and defined the first GOP as

$$\zeta_1 = 1 + \frac{1 - (11/7)\mathrm{log}P + (4/7)\mathrm{log}\dot{P}_{15}}{3.56 - \mathrm{log}P - \mathrm{log}\dot{P}_{15}}. \tag{6}$$

Wei et al. (1997) considered absorption of high energy photons by the effect of both magnetic and electric fields, defining the second GOP as,

$$\zeta_2 = 1 + \frac{0.8 - (2/7)\mathrm{log}P + (2/7)\mathrm{log}\dot{P}_{15}}{1.3}. \tag{7}$$

The concept of generation was initially considered in the scheme that the γ-ray photons are absorbed and converted into $\mathrm{e}^+/\mathrm{e}^-$ through magnetic fields only (Zhao et al. 1989), so we defined the third GOP based on the magnetic field absorption effects as (Wang & Zhao 2004)

$$\zeta_3 = 1 + \frac{0.6 - (11/14)\mathrm{log}P + (2/7)\mathrm{log}\dot{P}_{15}}{1.3}. \tag{8}$$

GOPs are used to describe cascade processes and characterize the spectral properties of pulsars. If a pulsar can emit gamma-rays, the GOPs must be larger than one (i.e., the first-generation gamma-ray photons must exist). In addition, the GOPs have been proved to be correlated with the gamma-ray photon index: pulsars with larger GOPs will emit softer gamma-ray photons based on the EGRET pulsar sample (Lu et al. 1994; Wei et al. 1997). Then, according to the definition of GOPs, the first-generation pairs emit high energy gamma-rays (i.e., $> 100\,\mathrm{MeV}$), with larger GOPs, so more first-generation pairs are transferred into next-generation pairs with lower energy, which emit more soft gamma-rays and X-rays. Given a total emission rate, the efficiency of GeV gamma-rays (η) becomes lower with larger GOPs.

In Figure 2, we plot the diagrams of η versus three GOPs (ζ_{1-3}). Here η has no correlation with ζ_1 but does have a correlation with the other two GOPs, ζ_2 and ζ_3, implying that magnetic fields dominate the absorption in pair cascade processes, which is consistent with our previous results (Wang & Zhao 2004). These correlations also suggest that GOPs (ζ_2, ζ_3) can describe the gamma-ray properties of pulsars. In Figure 2, the solid lines show the best fitting functions for the relations of $\eta - \zeta_2$ and $\eta - \zeta_3$

$$\log\eta = (4.98 \pm 0.45) - (3.00 \pm 0.21)\zeta_2 \tag{9}$$

with $\sigma \sim 1.69$ and a p-value of 1.94×10^{-4}

$$\log\eta = (5.49 \pm 0.24) - (2.86 \pm 0.11)\zeta_3 \tag{10}$$

with $\sigma \sim 1.34$ and a p-value of 1.01×10^{-6}. The correlation between $\eta - \zeta_3$ is stronger with the smaller standard deviation and p-value.

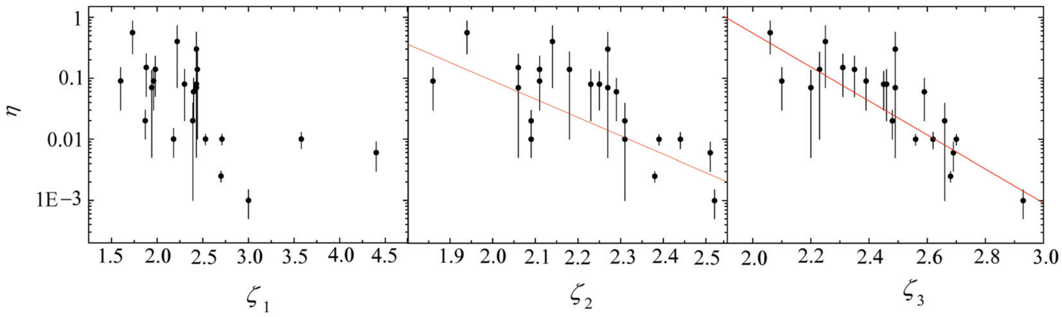

Fig. 2 Gamma-ray emission efficiency η of 21 young pulsars versus three-generation order parameters ζ_{1-3} in gamma-ray pulsars. Here η has no significant correlation with ζ_1 but has a correlation with ζ_2 and ζ_3, suggesting that the magnetic field dominates the gamma-ray absorption in cascade processes. The solid lines show the best fitting function. See the text for details.

3 POSSIBLE DISTANCE INDICATORS FOR GAMMA-RAY SELECTED PULSARS

In Section 2, the relations between η and six pulsar parameters: P, τ, $B_{\rm LC}$ and three GOPs ζ_1, ζ_2, ζ_3 are studied. From the values of standard deviation and p-values after fittings, the correlation of $\eta - \zeta_3$ is stronger than others and the correlation of $\eta - B_{\rm LC}$ could also be acceptable. In this paper, we do not consider the physical origin in these correlations. These pulsar parameters can be estimated by two fundamental measurement parameters, P and $\dot{P}$, which are relatively easily observed. The gamma-ray emission efficiency is sensitively dependent on distance measurement, which is very difficult at present, and nearly impossible for gamma-selected pulsars in particular. With the strong correlation of $\eta - \zeta_3$, we have a possible way to estimate a reliable distance for gamma-ray pulsars with only known values for P, $\dot{P}$ and F_γ.

In the catalog of Abdo et al. (2010), 17 gamma-selected pulsars are listed and most of them have no distance information. Saz Parkinson et al. (2010) claimed to have detected eight new gamma-selected pulsars in blind frequency searches of Fermi LAT data.

In Table 1, we use the distance indicator obtained by the $\eta - \zeta_3$ correlation to estimate the distances of the 25 gamma-selected pulsars. For comparison, we also give the predicted distance values calculated using the relation of $\eta - B_{\rm LC}$. From Table 1, we find that the evaluated distances $(d_1,\ d_2)$ by $\eta - \zeta_3$ and $\eta - B_{\rm LC}$ correlations are similar, suggesting that these two distance indicators can be checked with each other.

In Table 1, we also collected distance information (d_3) for some gamma-selected pulsars from other measurements or estimations. For the Geminga pulsar, we estimate the distance to be 0.19 ± 0.07 kpc, which is very consistent with the distance value of $0.25^{+0.12}_{-0.06}$ kpc from the optical trigonometric parallax measurement (Faherty et al. 2007). For PSR J1836+5925, we estimate its distance to be ~ 0.3 kpc (corresponding to an efficiency of $\sim 55\%$), which is also well below the upper limits of 0.8 kpc according to its thermal X-ray spectrum (Halpern et al. 2007). For other gamma-selected pulsars, our estimated distance values are generally below those from other methods, but may be more reliable. According to the distance estimated from the $\eta - \zeta_3$ relation, the gamma-ray efficiency η is generally below one. The estimated efficiency of PSR J2021+4026 is about ~ 0.16 (corresponding to $d \sim 0.4$ kpc) according to the $\eta - \zeta_3$ relation, compared to $\eta \sim 0.9 - 3.6$ (corresponding to a distance of 1 – 2 kpc) from the kinematic model method of the possible association (Landecker et al. 1980).

Table 1 Estimated Distances of 25 Gamma-selected Pulsars

Pulsar	P (s)	$\dot{P}$ ($\mathrm{s\,s^{-1}}$)	$F_\gamma(>100\,\mathrm{MeV})$ ($\mathrm{erg\,cm^{-2}\,s^{-1}}$)	d_1 (kpc)	d_2 (kpc)	d_3 (kpc)	Reference
J0007+7303	0.316	3.61×10^{-13}	3.82×10^{-10}	$0.86^{+0.30}_{-0.32}$	$1.18^{+0.72}_{-0.44}$	1.4 ± 0.3	Pineault et al. 1993
J0357+32	0.444	1.20×10^{-14}	6.38×10^{-11}	$0.72^{+0.25}_{-0.29}$	$0.73^{+0.51}_{-0.30}$		
J0633+0632	0.297	7.95×10^{-14}	8.00×10^{-11}	$1.26^{+0.41}_{-0.48}$	$1.37^{+0.76}_{-0.60}$		
J0633+1746	0.237	1.10×10^{-14}	3.38×10^{-9}	$0.19^{+0.07}_{-0.07}$	$0.17^{+0.09}_{-0.06}$	$0.25^{+0.12}_{-0.06}$	Faherty et al. 2007
J1418–5819	0.111	1.70×10^{-13}	2.35×10^{-10}	$1.39^{+0.58}_{-0.57}$	$1.86^{+1.09}_{-0.80}$	2–5	Ng et al. 2005
J1459–60	0.103	2.55×10^{-14}	1.06×10^{-10}	$1.76^{+0.70}_{-0.67}$	$1.62^{+0.97}_{-0.69}$		
J1732–31	0.197	2.62×10^{-14}	2.42×10^{-10}	$0.77^{+0.41}_{-0.35}$	$0.86^{+0.49}_{-0.30}$		
J1741–2054	0.414	1.69×10^{-14}	1.28×10^{-10}	$0.59^{+0.26}_{-0.25}$	$0.80^{+0.48}_{-0.29}$	0.38 ± 0.11	Camilo et al. 2009
J1809–2332	0.147	3.44×10^{-14}	4.13×10^{-10}	$0.78^{+0.31}_{-0.31}$	$0.81^{+0.48}_{-0.30}$	1.7 ± 1.0	Oka et al. 1999
J1813–1246	0.048	1.76×10^{-14}	1.69×10^{-10}	$2.18^{+0.71}_{-0.64}$	$1.56^{+1.21}_{-0.68}$		
J1826–1256	0.110	1.21×10^{-13}	3.34×10^{-10}	$1.29^{+0.56}_{-0.44}$	$1.39^{+0.86}_{-0.60}$		
J1836+5925	0.173	1.49×10^{-15}	5.99×10^{-10}	$0.32^{+0.13}_{-0.14}$	$0.27^{+0.15}_{-0.09}$	<0.8	Halpern et al. 2007
J1907+0602	0.107	8.68×10^{-14}	2.75×10^{-10}	$1.39^{+0.46}_{-0.40}$	$1.42^{+0.95}_{-0.61}$		
J1958+2846	0.290	2.10×10^{-13}	8.45×10^{-11}	$1.54^{+0.56}_{-0.51}$	$1.86^{+1.01}_{-0.78}$		
J2021+4026	0.265	5.48×10^{-14}	9.76×10^{-10}	$0.38^{+0.20}_{-0.21}$	$0.46^{+0.20}_{-0.18}$	1.5 ± 0.5	Landecker et al. 1980
J2032+4127	0.143	1.98×10^{-14}	1.11×10^{-10}	$1.32^{+0.49}_{-0.52}$	$1.33^{+0.71}_{-0.50}$	$1.6-3.6$	Camilo et al. 2009
J2238+59	0.163	9.86×10^{-14}	5.44×10^{-11}	$2.36^{+0.75}_{-0.70}$	$2.64^{+1.36}_{-0.93}$		
J1023–5746	0.111	3.84×10^{-13}	2.69×10^{-10}	$1.77^{+0.70}_{-0.55}$	$2.09^{+0.95}_{-0.88}$		
J1044–5737	0.139	5.46×10^{-14}	1.03×10^{-10}	$1.72^{+0.60}_{-0.65}$	$1.86^{+0.86}_{-0.72}$		
J1413–6205	0.110	2.78×10^{-14}	1.29×10^{-10}	$2.52^{+0.89}_{-0.92}$	$1.56^{+1.12}_{-0.60}$		
J1429–5911	0.116	3.05×10^{-14}	9.26×10^{-11}	$1.84^{+0.64}_{-0.69}$	$1.79^{+0.97}_{-0.70}$		
J1846+0919	0.226	9.92×10^{-15}	3.58×10^{-11}	$1.52^{+0.55}_{-0.70}$	$1.44^{+0.80}_{-0.51}$		
J1954+2836	0.093	2.12×10^{-14}	9.75×10^{-11}	$1.90^{+0.67}_{-0.80}$	$1.72^{+1.10}_{-0.71}$		
J1957+5033	0.375	7.08×10^{-15}	2.27×10^{-11}	$1.22^{+0.41}_{-0.45}$	$1.31^{+0.65}_{-0.37}$		
J2055+2500	0.320	4.08×10^{-15}	1.15×10^{-10}	$0.56^{+0.19}_{-0.23}$	$0.61^{+0.30}_{-0.19}$		

Notes: d_{1-2} denotes the distance range calculated from relations of $\eta-\zeta_3$ and $\eta-B_{\rm LC}$, respectively. d_3 is the estimated distance from other methods with references provided.

4 SUMMARY AND DISCUSSION

In this article, we studied the possible correlations between gamma-ray emission efficiency η and six pulsar parameters: P, τ, $B_{\rm LC}$ and three generation order parameters ζ_{1-3} using 21 young radio-selected gamma-ray pulsars in Abdo et al. (2010). We find a strong correlation between $\eta-\zeta_3$. Based on the concept of the GOPs, larger GOPs imply that more high energy photons are transformed to softer photons (X-rays). The good correlation of $\eta-\zeta_3$ suggests that GOPs can describe gamma-ray emission properties of young pulsars, and that the magnetic field absorption effects dominate pair cascade processes in a pulsar magnetosphere. This intrinsic correlation can be used to estimate distances for gamma-selected pulsars, which have no distance information yet. The good correlation of $\eta-B_{\rm LC}$ is also found, which can also be used as another distance indicator in gamma-ray pulsars for double-checking purposes.

Millisecond pulsars (MSPs) have not been included in our analysis, although their distances are generally measured by optical trigonometric parallax and DM methods. MSPs with much smaller P and $\dot{P}$ have a much older characteristic age ($\tau\sim10^9$ yr). The values of ζ_1 and ζ_2 are below one or near one, making MSPs non-gamma pulsars if these two GOPs are still applicable to MSPs.

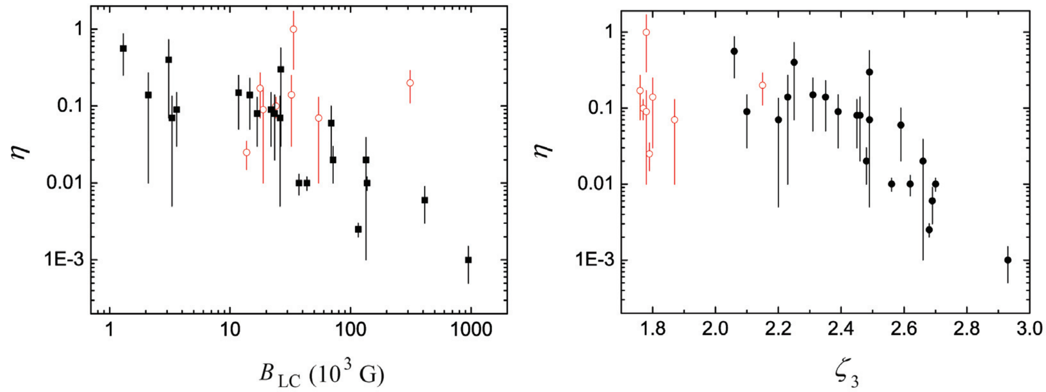

Fig. 3 Gamma-ray emission efficiency η versus $B_{\rm LC}$ and ζ_3 for both 21 young gamma-ray pulsars (solid circles) and 8 millisecond gamma-ray pulsars (open circles). Millisecond pulsars still generally follow the relations of $\eta - B_{\rm LC}$ and $\eta - \zeta_3$ in young pulsars, but they may have a nearly constant gamma-ray radiation efficiency of $\eta \sim 10\%$.

However, in parameter spaces of $B_{\rm LC}$ and ζ_3, MSPs are similar to young pulsars. In Figure 3, we plot the diagrams of $\eta - B_{\rm LC}$ and $\eta - \zeta_3$ including both 21 young pulsars and 8 MSPs in the first gamma-ray pulsar catalog (Abdo et al. 2010). MSPs seem to still follow the behavior of young pulsars: higher efficiency with smaller values of $B_{\rm LC}$ and ζ_3. At the same time, the gamma-ray emission efficiency of MSPs are also be believed to remain constant at $\eta \sim 10\%$ (also see fig. 6 of Abdo et al. 2010). So, MSPs may have different gamma-ray emission properties from young pulsars, like the multi-pole magnetic field assumption in MSPs (Ruderman 1991; Zhang & Cheng 2003), or different emission open angles (taken as $f_\Omega \sim 0.5$, Fierro et al. 1995). Current discoveries of MSPs are generally done through radio timing, and the blind search for MSPs by Fermi/LAT is a very important future project, but quite difficult at present, especially for MSPs in binaries. Then the distance indicators of $\eta - B_{\rm LC}$ and $\eta - \zeta_3$ relations could be a secondary way to obtain distance information of MSPs after trigonometric parallax or DM methods.

The GOP model was originally proposed based on the polar-cap accelerator scenario. The present Fermi/LAT may support that gamma-ray emission in pulsars mainly comes from the spatially extended regions reaching a good fraction of the light-cylinder radius (e.g., Abdo et al. 2010). The production of the secondary pairs in polar-cap activity is also different from that in scenarios of outer-gap models or slot-gap models (e.g., Cheng et al. 2000; Muslimov & Harding 2004; Yu et al. 2009). Then a new model of generation-order parameters could be developed in the extended regions from the polar-cap regions to near the light-cylinder radius. This GOP model would be more complicated but could be considered in the next work. The correlations of $\eta - \zeta_3$ and $\eta - B_{\rm LC}$ for gamma-ray pulsars suggest that gamma-ray luminosity may depend on two fundamental pulsar parameters: P and $\dot{P}$. The function of P and $\dot{P}$ could predict gamma-ray emission luminosity well, which can be used to trace the distance of gamma-ray pulsars.

Figure 4 shows the distance distributions of three classes of gamma-ray pulsars: gamma-selected pulsars, radio-selected pulsars and millisecond pulsars. The distances of gamma-selected pulsars are provided by the distance indicator of the $\eta - \zeta_3$ relation (see Table 1). Gamma-ray loud millisecond pulsars are distributed with a distance peak around 0.3 kpc because MSPs generally have lower spin-down powers. Gamma-selected young pulsars are distributed with a distance peak of $\sim$ 1.2 kpc, while radio-selected young pulsars are distributed with a distance peak of $\sim$ 2.5 kpc. This difference

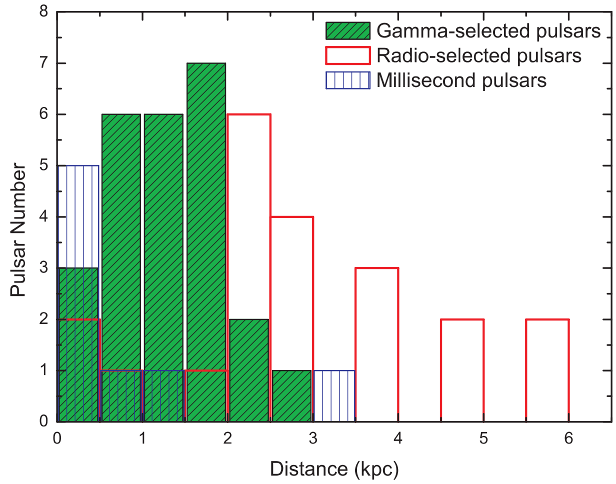

Fig. 4 Distance distributions of three classes of gamma-ray pulsars: gamma-selected pulsars, radio-selected pulsars and millisecond pulsars. The distances of gamma-selected pulsars are taken from the column d_1 of Table 1 according to the distance indicator of the $\eta - \zeta_3$ correlation.

in distance distributions for two classes of gamma-ray young pulsars may pique further interest. The nearby unresolved radio-quiet gamma-ray pulsars could contribute to both the electron/positron background flux and diffuse gamma-ray background, especially for high-latitude pulsars located in the Gould Belt (Wang et al. 2005).

Before the Fermi era, only one gamma-selected pulsar, Geminga, was known. Now 25 gamma-selected pulsars have been discovered, greatly improving our knowledge of the gamma-ray pulsar family. More gamma-selected pulsars could be detected by future deeper sky surveys using Fermi/LAT. The distance indicators presented in this paper will provide distance information for gamma-selected pulsars, which will be helpful for studies of the gamma-ray emission properties of this pulsar population. It is still expected that more (young) gamma-ray pulsars will have measurable trigonometric parallax values, which can lead to a more precise DM model. This can check the validity of the distance indicators (i.e., $\eta - \zeta_3$, $\eta - B_{\rm LC}$) and improve the distance indicators in gamma-ray pulsars.

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