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Fermi γ-Ray Pulsars: Spectral and Generation Order Parameters *

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We examine the theory of generation order parameters. Three kinds of generation order parameters are introduced, which describe the production of high-energy γ photons in a cascade process scenario. We find a correlation between the average power-law photon index Γ and spin-down rate $\dot{P}$ in 38 common FERMI γ-ray pulsars, and find that the third generation order parameter, which implies that the magnetic field may have the most significant effect on the high-energy γ photon absorption in the cascade processes, is the best one. The statistical work shows that the theory of generation order parameters can be applied to describe the the γ-ray pulsar radiation mechanisms in the cascade processes.

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Most γ-ray photons coming from space are absorbed by the Earth's atmosphere, so gamma-ray astronomy could not develop prosperously until it was possible to place detectors above all or most of the atmosphere using balloons or spacecraft.[1−3] Before the successful launch of the Fermi Gamma-ray Space Telescope (formerly GLAST), only seven γ-ray pulsars were known.[4]

The Large Area Telescope (LAT), the primary instrument on the Fermi mission, is an imaging, wide-field-of-view, high-energy γ-ray telescope, covering the energy range from below 20 MeV to more than 300 GeV. It can make an entire sky search every 3 hours.[5,6] Through the observations of the first 6 months, researchers found 40 previously unknown γ-ray pulsars,[7] providing a major increase in the known γ-ray pulsar population, including pulsars first discovered in gamma-ray[8] and millisecond γ-ray pulsars (MSGPs).[9]

We introduce the concept of the generation order parameter (GOP), which originally described the cascade processes of γ-ray pulsars.[10,11] Using this concept, Lu *et al.*[11] and Wei *et al.*[12] performed research based mainly on pulsar data from the Energetic Gamma Ray Experiment Telescope (EGRET). It has been found that the GOPs are correlated with the γ-ray spectral index Γ. The power-law γ-ray emission components of spin-powered pulsars are attributed to non-thermal emission processes coming from relativistic particles accelerated in a pulsar magnetosphere, whose energy originates from the pulsar's rotational energy loss. Therefore, spectral properties may be closely related to a pulsar's spin characteristics.

The 46 FERMI pulsars include 38 common gamma-ray pulsars (CGPs) and 8 MSGPs, among which 3 are solitary and 5 are in binaries. We find an interesting correlation in the CGPs which is the photon index Γ of spin-down γ-ray pulsars and becomes larger with the spin-down rate $\dot{P}$ increasing, though with a large dispersion, as shown in Fig. 1. This illustrates that FERMI pulsars with a high value of $\dot{P}$ converse more rotational energy to high-energy radiation. This may mean that the formation mechanisms of the 38 CGPs and 8 MSGPs that exist in the different regions in Fig. 1 are different. We only focus on the 38-CGP data because some processes, such as the formation mechanisms, of these two kinds of pulsars may be different. Thus it is difficult to find a Γ–$\dot{P}$ relation for all FERMI pulsars.

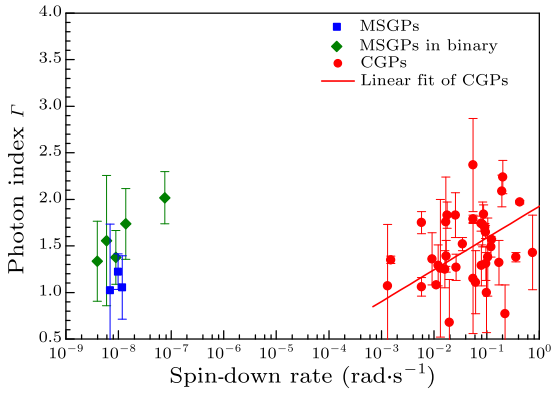


Fig. 1. The variation of power-law photon index Γ versus spin-down rate for the 46 FERMI pulsars. The x axis is the logarithm value of the FERMI pulsars' spin-Down rate, the y axis is the value of the FERMI pulsars' photon index Γ. The red oblique line is the linear fit of the photon index Γ versus the spin-down rate of the 38 CGPs.

Similar to Wang and Zhao,[13] we let the photon index be functions of P and $\dot{P}$, i.e., $\Gamma(P,\dot{P}) = \alpha \log P + \beta \log \dot{P} + \gamma$, and use it to fit the 38 CGPs with the result being

$$\Gamma(P,\dot{P}) \approx (-0.458 \pm 0.200)\log P + (0.1489 \pm 0.091)\log \dot{P}_{15} + (0.827 \pm 0.231), \quad (1)$$

where P is the period of the pulsar in units of second, $\dot{P}_{15}$ the derivative in units of $10^{-15}\mathrm{s\,s^{-1}}$. The right-hand side of Eq. (1) has a similar term to the definition of GOPs in the following. There should exist a pos-

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sible relation between photon indexes Γ and GOPs ζ for spin-powered γ-ray pulsars, and we can examine the theory of GOPs by searching the relations between the photon index Γ and the GOPs ζ. Later we will show that the theory of GOPs does not depend on the details of the pulsar radiation model. Thus the definition of GOPs based on any model should obtain the same statistical results and we can examine this theory in some simple cases. Therefore, we perform some analyses similar to Lu *et al.*[11] In that scenario it seems helpful to illustrate the concept of GOPs in cascade processes.[10,14,15] As carried out earlier by Wei, Song, and Lu,[12] for simplicity, we suppose that the pair cascade processes are initiated by curvature radiation.[14,16,17]

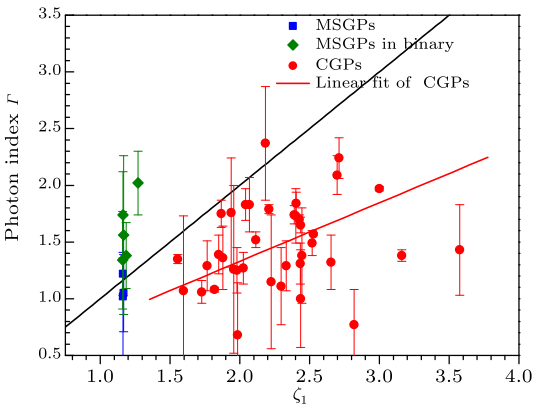


Fig. 2. Photon index Γ versus GOP ζ_1. The black oblique line denotes the value of horizontal coordinates equal to the value of vertical coordinates (the same in the following figures). The red oblique line is the 38 CGPs' linear fitting of the photon index Γ versus the generation order parameter ζ_1.

Now we introduce a general scenario of γ-ray radiation production in the magnetosphere near the pulsar's polar region. After the electrons (positrons) are accelerated to very high energies when they go though the vacuum polar gap where the potential difference between its base and top are up to 10^{12} volts, they will get a typical Lorentz factor $\gamma_1 = 6.0 \times 10^7 P^{1/14} \dot{P}_{15}^{-1/14}$. Then these electrons (positrons) move along the curved magnetic field lines and emit high energy curvature radiation (the first generation photons), with photon energy typically concentrated at

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

where $R_c \approx 1.8 \times 10^7 P^{1/2}$ cm is the curvature radius of the magnetic field line there. According to Hardee,[18] γ-ray photon energy higher than the critical energy

$$E_a = 9.5 \times 10^9 P^{1/2} \dot{P}_{15}^{-1/2} \mathrm{eV} \quad (3)$$

will be absorbed by the strong electromagnetic fields and transformed again into e^+/e^- pairs (the second generation e^+/e^- pairs). The Lorentz factor γ_2 of the second generation e^+/e^- pairs will be $E_c/2\mathrm{m_e c^2}$. These second generation e^+/e^- pairs can emit second generation photons through synchrotron radiation with a characteristic energy E_2. If $E_2 > E_a$, further e^+/e^- pairs can be produced in the magnetosphere. Thus, the cascade processes occur.

It is worth noticing that from one generation to the next, the photon energy values would decrease about 20 times,[10] while their spectra in turn become softer. Thus $E_1 = E_c = E_a 20^n$, where n is the generation of the γ-ray photons. Because the energy of γ-ray photons decreases dramatically, its energy would quickly become smaller than E_a only through very few generations. The most important thing is that this scenario of high-energy γ-ray photon radiation mechanism is rather general and might not depend upon details of the pulsar radiation model and makes the theory of GOPs very useful and fruitful.

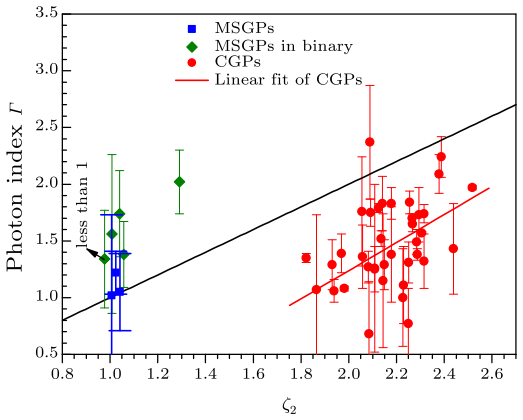


Fig. 3. Photon index Γ versus GOP ζ_2. The red oblique line is the 38 CGPs' linear fitting of the photon index Γ versus the generation order parameter ζ_2.

Based on the concept of generation, Lu *et al.*[11] introduced the GOP to characterize a pulsar' high-energy radiation mechanisms. Considering the conversion of high-energy photons γ-ray into e^+/e^- pairs under the case that electric fields play a major role, they defined the GOP as

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

Wei *et al.*[12] thought that both magnetic and electric fields are effective in high-energy γ-ray photons absorption. They defined another GOP as

$$\zeta_2 = 1 + \frac{0.8 - (2/7)\log P + (2/7)\log \dot{P}_{15}}{1.3}. \quad (5)$$

The concept of generation was initially considered in the scheme that the γ-ray photons can be absorbed and conversed into e^+/e^- through only magnetic fields.[10] In that mode, Zhao and Wang defined a GOP that only considers the effect of magnetic fields,

i.e.

$$\zeta_3 = 1 + n = 1 + \frac{0.6 - (11/14)\log P + (2/7)\log \dot{P}_{15}}{1.3},$$
$$E_1 = E_c = E_a 20^n. \quad (6)$$

Then we plot the diagrams of the GOPs $\zeta_{1,2,3}$ versus photon index Γ of FERMI γ-ray pulsars and try to search for the relation of ζ–Γ, see Eq. (1).

Table 1. The characteristics of 46 FERMI γ-ray pulsars. The first column is the FERMI pulsar name. Then ζ_1, ζ_2 and ζ_3 are the GOPs with three different definitions.[7]

PSR	ζ_1	ζ_2	ζ_3
J0007+7303	3.16	2.29	2.33
J0030+0451	1.16	1.02	1.76
J0205+6449	2.7	2.38	2.68
J0218+4232	1.27	1.29	2.15
J0248+6021	2.22	2.14	2.25
J0357+32	1.77	1.93	1.91
J0437−4715	1.16	1.04	1.75
J0534+2200	3	2.52	2.93
J0613−0200	1.19	1.06	1.87
J0631+1036	2.44	2.18	2.23
J0633+0632	2.33	2.15	2.2
J0633+1746	1.82	1.98	2.07
J0659+1414	2.18	2.09	2.09
J0742−2822	1.94	2.06	2.2
J0751+1807	1.17	1.01	1.8
J0835−4510	2.53	2.31	2.56
J1028−5819	1.98	2.11	2.35
J1048−5832	2.43	2.25	2.45
J1057−5226	1.73	1.94	2.06
J1124−5916	3.58	2.44	2.62
J1418−6058	2.65	2.32	2.53
J1420−6048	2.4	2.29	2.59
J1459−60	2.07	2.14	2.37
J1509−5850	1.88	2.06	2.31
J1614−2230	1.16	0.98	1.78
J1709−4429	2.43	2.27	2.49
J1718−3825	1.96	2.11	2.39
J1732−31	2.02	2.08	2.2
J1741−2054	1.85	1.97	1.96
J1744−1134	1.16	1.01	1.77
J1747−2958	2.3	2.23	2.46
J1809−2332	2.12	2.14	2.3
J1813−1246	2.04	2.18	2.53
J1826−1256	2.52	2.28	2.5
J1833−1034	2.71	2.39	2.7
J1836+5925	1.55	1.82	1.96
J1907+06	2.4	2.26	2.47
J1952+3252	1.87	2.09	2.48
J1958+2846	2.82	2.25	2.3
J2021+3651	2.43	2.27	2.49
J2021+4026	2.21	2.12	2.19
J2032+4127	1.99	2.09	2.26
J2043+2740	1.6	1.86	2.1
J2124−3358	1.17	1.04	1.78
J2229+6114	2.39	2.31	2.66
J2238+59	2.43	2.23	2.38

The values of $\zeta_{1,2,3}$ are listed in Table 1. In Figs. 2 and 3, the CGPs and MSGPs locate on different regions. The red oblique line is only the linear fitting of the 38 CGPs. In Fig. 4, the CGPs and MSGPs almost distribute throughout the map evenly, and the red oblique line is the linear fitting of all the 46 FERMI pulsars. This reflects that the theory of GOPs might not depend upon the details of the model, just as we mentioned earlier in this Letter. The three $\zeta_{1,2,3}$–Γ relations' linear fitting results are shown by Eqs. (7), (8) and (9), respectively.

$$\Gamma \approx (0.193 \pm 0.142)\zeta_1 + (1.037 \pm 0.328). \quad (7)$$

$$\Gamma \approx (0.938 \pm 0.372)\zeta_2 - (0.562 \pm 0.810). \quad (8)$$

$$\Gamma \approx (0.472 \pm 0.176)\zeta_3 - (0.396 \pm 0.401). \quad (9)$$

These figures all show possible correlation between GOPs ζ and photon indexes Γ. The photon index Γ becomes larger with the increasing GOP ζ. Although the error bar of the fitting results is relatively large, the main trend is obvious. The large error bar may be caused by the data of γ-ray pulsars that is still so little. The photon index value of the MSGPs are relatively smaller, and we can use the GOPs' values to distinguish different kinds of γ-ray pulsars. Notice that the ζ_2 value of the pulsar (J1614-2230) is less than 1. Actually this value is debated, because theocratically one γ-ray pulsar with a GOP less than 1 would radiate very little high-energy photons that could be potentially undetectable. Then the definition of the ζ_2 may have some problems. We remark that ζ_3–Γ shows the better correlation than ζ_1–Γ and ζ_2–Γ. Nearly all the 46 FERMI pulsars appear under the black oblique line in the figure of ζ_3–Γ. According to the definitions of the third GOP ζ_3, we draw a conclusion that in FERMI γ-ray pulsars, magnetic field may have the most significant effect on the high-energy photons' absorption during cascade processes, which is also consistent with the conclusion of a theoretical work by Zheng, Zhang and Qiao.[19]

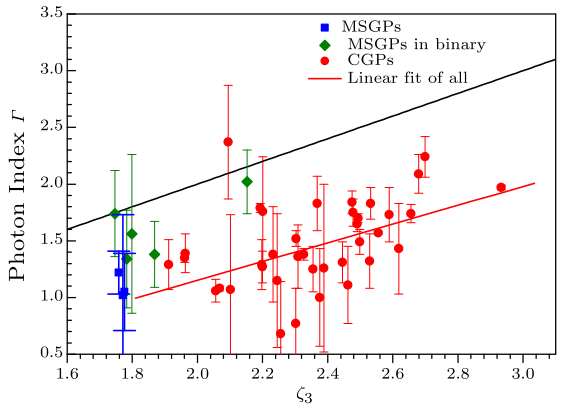


Fig. 4. Photon index Γ versus GOP ζ_3. Unlike in Figs. 2 and 3, the red oblique line is all the 46 FERMI pulsars' linear fitting of the photon index Γ versus the generation order parameter ζ_3.

In summary, based on the FERMI pulsar data, we have studied the relation between the average power-law photon index Γ and the spin-down rate $\dot{P}$, and investigated the relations between three kinds of GOPs

$\zeta_{1,2,3}$ with the photon index Γ. Firstly, we find a correlation between the average power-law photon index and the spin-down rate in 38 CGPs: the photon index Γ of spin-down γ-ray pulsars becomes larger with the increasing spin-down rate $\dot{P}$. Secondly, considering that the scenario of high-energy γ-ray photon production mechanism is rather general and might not depend upon the details of the model, we examine the theory of GOPs through a simplified case that is based on the R-S model. We obtain a general conclusion based on the definition of the third GOP, which suggests that in γ-ray pulsars the conversion of high-energy γ photons into e^+/e^- pairs through magnetic fields is the dominant mechanism over the electric field.

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