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Which unidentified EGRET sources are gamma-ray pulsars?

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Abstract. We consider high energy γ-ray radiation from the radio pulsars associated with some unidentified EGRET γ-ray sources. Calculated efficiencies for the conversion of spin-down power to γ-rays and the energy spectra of the high energy γ-rays from these possible γ-ray pulsars in outer gap models are compared with observed results. Of these possible γ-ray pulsars, our results indicate that (i) PSR B1900+05 is not a possible γ-ray pulsar; (ii) although the newly discovered young radio pulsar PSR J1105-6107 is a possible γ-ray pulsar, it may not account for the observed high energy γ-ray emission from 2EG J1103-6106; (iii) the high energy γ-rays from 2EG J1801-2312 and 2EG J1857+0118 may not be produced completely by radio pulsars PSR B1758-23 and PSR B1853+01 respectively; (iv) the counterparts (radio pulsars PSR B1046-58 and PSR B1823-13) of 2EG J1049-5247 and 2EG J1825-1307 are possible γ-ray pulsars; and (v) 2EG J0008-7307 associated with a young supernova remnant CTA 1 may contain a γ-ray pulsar with period $0.16 \geq P \geq 0.12$ s.

Key words: gamma rays: theory – stars: pulsars: general – stars: neutron

1. Introduction

Since the launch of the Compton Gamma-Ray Observatory (CGRO) about 35 EGRET γ-ray point sources within $|b| < 10°$ of the Galactic plane have been observed by EGRET (Thompson et al 1995, 1996). The nature of these unidentified γ-ray sources is an outstanding question. Halpern & Ruderman (1993) and Helfand (1994) pointed out that all unidentified Galactic γ-ray sources could be pulsars. Although a different conclusion was given by Mukherjee et al. (1995), it has been argued that most of the unidentified Galactic γ-ray sources are expected to be Geminga-like pulsars (Yadigaroglu & Romani 1995). Furthermore, Kaaret & Cottam (1996) searched for the correlation between the positions of unidentified Galactic γ-ray sources and OB star association and found that 16 of 25 EGRET γ-ray sources lie in or near OB star associations. They found that the luminosity function is consistent with the known γ-ray pulsars if the distances of the unidentified Galactic γ-ray sources are those of the OB star associations. Hence they concluded that a majority of the unidentified Galactic γ-ray sources are probably pulsars. Yadigaroglu & Romani (1997) extented this analysis. They used up-to-date catalogs of EGRET sources and of OB star associations, supernova remnants (SNRs), young pulsars, H II regions and young open clusters to find the correlation between them, and found that 22 of 35 EGRET sources are coincident with young objects. Of these 22 EGRET sources, 5 counterparts are probably young pulsars. Therefore, they inferred that young pulsars can account for essentially all of the excess low latitude EGRET sources. More recently, a newly discovered radio pulsar PSR J1105-6107 was found to be coincident with EGRET source 2EG J1103-6106 (Kaspi et al 1997). Supernova remnant CTA 1 may contain a pulsar (Slane et al 1997) and is the most likely counterpart of 2EG J0008+7307 (Brazier et al 1997). In summary, *at present* there are 7 pulsars which may be the counterparts of the EGRET unidentified γ-ray sources.

If high energy γ-ray emission from the unidentified EGRET sources is from γ-ray pulsars, then we can use parameters such as the period and magnetic field of these pulsars to calculate their expected high energy radiation based on particular models for high energy γ-ray emission, compare them with the observed corresponding EGRET sources and then determine whether these unidentified EGRET sources can be associated with these pulsars if these models are correct. This is the purpose of this paper. In Sect. 2, we describe the basic observed properties of the 7 pulsars. In Sect. 3, we give a brief review of γ-ray pulsar model which we use. Expected results are shown in Sect. 4 and a brief discussion is given in Sect. 5.

2. Possible gamma-ray pulsars associated with unidentified EGRET sources

Sturner & Dermer (1995) have proposed a test to search for coincidences between unidentified γ-ray sources with supernova remnants (SNRs). Yadigaroglu & Romani (1997) extended Sturner & Dermer's test to allow a general search for counterparts. They defined a probability $Prob$ that characterizes the likelihood for counterparts of γ-ray sources occurring by chance. The counterpart for an EGRET source is considered as an "identified" source if $Prob < 3\%$; otherwise it is considered to be an overlapping object. In the catalog of unidenti-

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fied EGRET γ-ray sources and coincident young objects given by Yadigaroglu & Romani (1997), three radio pulsars PSR B1046-58, PSR B1758-23 and PSR B1900+05 are thus identified as counterparts of 2EG J1049-5847, 2EG J1801-2312 and 2EGS J1903+0529. Kaaret & Cottam (1996) suggested that PSR B1853+01 is the counterpart of 2EG J1857+0118 (also see Fierro 1995). Fierro (1995) suggested that PSR B1823-13 should be the counterpart of 2EG J1801-2312. For 2EG J1801-2312 and 2EG J1857+0118, although Yadigaroglu & Romani (1997) suggested that their counterparts are probably HII S 53 and SNR W44, they are identified as overlapping objects with the above criterion. PSR B1823-13 and PSR B1853+01 are also probably the counterparts of 2EG J1801-2312 and 2EG J1857+0118 respectively. Furthermore, Kaspi et al (1997) reported the discovery of radio pulsar PSR J1105-6107 with a period of 63 ms and a surface magnetic field 10^{12} G. Considering its possible association with the supernova remnant MSH 11-61A, they pointed out that this pulsar is a possible counterpart of 2EG J1103-6106. Brazier et al (1997) have also proposed that there is a possible young γ-ray pulsar in supernova remnant CTA 1 which may be a radio-quiet pulsar, and is the most likely counterpart of 2EG J0008+7307. In Table 1, we list these possible γ-ray pulsars and the corresponding EGRET sources, where the observed flux and spectral index (except for 2EGS J1903+0529) for each source are also listed. We list the basic properties of these possible γ-ray pulsars in Table 2. Of these possible γ-ray pulsars, six are radio pulsars. Except for PSR J1105-6107 (its basic properties are given by Kaspi et al (1997)), their basic properties such as periods, surface magnetic fields and distances can be found in Taylor, Manchester & Lyne (1993). Using the observed flux and spectral index, the observed luminosity can then be obtained and the observed conversion efficiency of spin-down power into γ-rays, defined as the observed luminosity divided by the spin-down power, can be deduced. In Table 2 and Fig. 2, the observed conversion efficiencies are also shown by assuming a beam solid angle of 1 steradian for the radio pulsars except for PSR B1900+05 (its spectral index is not known).

The basic properties of the possible γ-ray pulsar in the SNR CTA 1 suggested by Slane et al (1997) is also listed in Table 2. Generally, it is believed that supernovae produce neutron stars which are expected to be pulsars as well. At present, there are 18 known radio pulsars associated with supernova remnants (Gorham et al 1996). Seward & Wang (1988) developed an empirical relationship between the X-ray luminosity from the supernova (L^s_X) and the pulsar's spin-down power ($\dot{E}$) based on X-ray observations of SNRs and radio pulsars: $\log L^s_X = 1.39 \log \dot{E} - 16.6$. From this relationship, the period and magnetic field of a pulsar in a SNR can be estimated if its X-ray flux is observed and the SNR's age is known. For the possible pulsar in the SNR CTA 1, using the total observed X-ray flux from the supernova, $L^s_X \approx 5.6 \times 10^{33} d^2_{1.4}$ ergs s^{-1}. From the empirical relationship derived by Seward & Wang (1988) and the SNR age, $t = 2.0 \times 10^4 d_{1.4}$ yr, where $d_{1.4}$ is the remnant distance in units of 1.4 kpc, Slane et al (1997) derived a period of 0.14 s and a surface magnetic field of 3.9×10^{12} G. Recently, Becker & Trümper (1997) have given a new empirical relationship between the X-ray luminosity of a pulsar (L^p_X) and $\dot{E}$ from recent X-ray observations of 27 pulsars by ROSAT and ASCA: $\log L^p_X = \log \dot{E} - 3$. Based on the pulsar model proposed by Zhang & Cheng (1997), Cheng, Gil & Zhang (1997) have proposed that the X-ray luminosity from pulsar can be expressed as

$$\log L^p_X = \log \dot{E} - 3.26 + 4 \log \left(\frac{\tan \chi}{\tan 55^\circ} \right) + 0.13 \log B_{12} - 0.8 \log P \ , \qquad (1)$$

where χ is the inclination angle of the pulsar, B_{12} is the magnetic field in 10^{12} G and P is the period in seconds. For SNR CTA 1, the observed X-ray flux from circular region of radius $9'.2$ centered on the bright central region is $F_X = 9.5 \times 10^{-12}$ ergs cm^{-2}s^{-1}. The corresponding X-ray luminosity is assumed as $L^p_X \approx 2.2 \times 10^{33}$ ergs s^{-1}. Using the empirical relationship given by Becker & Trümper (1997), we find $P \approx 0.12 d^{-1.5}_{1.4}$ s and $B_{12} \approx 3.4 d^{-1.9}_{1.4}$ respectively. Using Eq. (2), we have $P \approx 0.16(\tan\chi/\tan 55^\circ)^{1.5}\ (\sin\chi/\sin 55^\circ)^{0.75} d^{-1.15}_{1.4}$ s and $B_{12} \approx 4.6(\tan\chi/\tan 55^\circ)^{1.5}\ (\sin\chi/\sin 55^\circ)^{0.75} d^{-1.65}_{1.4}$ all of which are different from those given by Slane et al (1997) ($\dot{E} \approx 2.6 \times 10^{31} P^{-4} B^2_{12}\ (\sin\chi/\sin 55^\circ)^2$ has been used in our calculation). Therefore, for the possible γ-ray pulsar in SNR CTA 1, we use different values of period and magnetic field in our following calculations. The observed conversion efficiency, which is the ratio between the γ-ray power and the spin-down power, is $(0.24 \pm 0.12) \times 10^{-2}$ for $P = 0.12$ s and $B_{12} = 3.4$; $(0.34 \pm 0.13) \times 10^{-2}$ for $P = 0.14$ s and $B_{12} = 3.9$; $(0.69 \pm 0.27) \times 10^{-2}$ for $P = 0.16$ s and $B_{12} = 4.6$ (where $\chi = 55^\circ$ is assumed). These values are also shown as empty boxes in Fig. 2.

It is interesting to consider the spectral indices of γ-ray radiation for these EGRET sources. Merck et al (1996) studied the spectral characteristics of the unidentified galactic EGRET sources. They fitted the energy spectra for these EGRET sources by assuming power-law distributions. We take the spectral indices for these seven EGRET sources from their analysis. For the 6 known γ-ray pulsars, Nolan et al (1996) have also given spectral indices. Their results indicate that the spectral indices of the known γ-ray pulsars are typically below 2.0 except for very young Crab pulsar whose spectral index is 2.07. So it is expected that a possible γ-ray pulsar should have a γ-ray spectral index ≤ 2.0 (Merck et al. 1996), except for very young pulsars such as the Crab pulsar. In Fig. 1, we show the spectral index versus characteristic age for the known γ-ray pulsars (solid circles) and the possible γ-ray pulsars (empty circles). In Fig. 1, we can see that the spectral indices of possible pulsars with characteristic age $\geq 10^4$ years are not greater than 2.0 except for 2EG J1103-6106 whose spectral index is 2.3 ± 0.1. However, it may not mean that PSR J1105-6107 is not a possible γ-ray pulsar because of its poor energy spectral data.

Table 1. Unidentified EGRET sources near pulsars

EGRET source	l (deg)	b (deg)	Flux^a	α^b	coincident pulsar
2EG J0008-7307	119.8	10.5	46.4 ± 6.2	1.58 ± 0.20	CTA 1[1]
2EG J1049-5847	287.6	0.4	59.7 ± 8.7	2.0 ± 0.1	PSR B1046-58[2]
2EG J1103-6106	290.3	-0.9	56.3 ± 9.0	2.3 ± 0.2	PSR J1105-6107[3]
2EG J1825-1307	18.4	-0.4	62.3 ± 9.7	2.0 ± 0.1	PSR B1823-13[2,4]
2EG J1857+0118	34.8	-0.8	41.8 ± 10.1	1.90 ± 0.2	PSR B1853+01[2]
2EG J1801-2312	6.7	-0.1	55.1 ± 8.7	1.9 ± 0.2	PSR B1758-23[2,4]
2EGS J1903+0529	39.1	-0.1	45.3 ± 9.0	...	PSR B1900+05[2]

a: Average flux for $E_\gamma > 100$ MeV in units of 10^{-8} photons cm^{-2}s^{-1}.
b: Spectral index, for differential photon flux $\propto E^{-\alpha}$.

(1) Brazier et al (1997); (2) Yadigaroglu & Romani (1997); (3) Kaspi et al (1997); (4) Kaaret & Cottam (1996).

Table 2. Basic features of possible γ-ray pulsars in our model.

Pulsar	P(ms)	$B_{12}(G)$	age (10^5 yr)	d (kpc)	η_γ^{ob}% ^{a}	$F_\gamma^{th\ b}$
CTA 1	140.0	3.9	0.2000	1.4 ± 0.3	0.33 ± 0.15	124.0 ± 26.6
B1046-58	123.7	3.5	0.2042	3.0 ± 0.6	0.93 ± 0.25	27.2 ± 5.4
B1758-23	415.8	6.9	0.5843	3.0 ± 0.8	38 ± 11	22.0 ± 5.8
B1823-13	101.0	2.8	0.2143	4.1 ± 1.0	1.60 ± 0.40	14.4 ± 3.6
B1853+01	267.0	7.5	0.2032	3.3 ± 0.8	7.4 ± 2.3	22.4 ± 5.4
B1900+05	746.6	3.1	9.162	$3.9^{+4.8}_{-2.7}$	...	...
J1105-6107	63.2	1.0	0.6335	7.0 ± 1.3	2.9 ± 0.1	4.0 ± 0.8

a: η_γ^{ob} is the conversion efficiency by assuming the beaming angle of 1 steradian.
b: The values from Eq. (16) are in units of 10^{-8} cm^{-2}s^{-1} with $\Delta\Omega_\gamma = 1.0$ sr.

3. High energy gamma-ray emission from pulsars

There are generally two kinds of models for high energy emission from pulsars, namely polar gap and outer gap models. Both models give observed features of the known γ-ray pulsars. In the polar gap models, charged particles are accelerated in charged-depleted zones near pulsar's polar cap and high energy γ-rays are produced through curvature radiation induced γ-B pair cascades (e.g. Harding 1981) or through Compton-X-ray induced pair cascades (Dermer & Sturner 1994). In the outer gap models, large regions of magnetospheric charge depletion (gaps) are assumed to result from the plausible global current flow pattern through the magnetosphere and charged particles in them, which are expected to be electrons/positrons are accelerated to extreme relativistic energies because of large electric field along the magnetic lines in these gaps. In previous outer gap models, the outer gap is generally assumed to be thin (we call it as thin outer gap model). In such models the observed γ-rays are synchrotron radiation (Vela-type) or synchrotron plus self-Compton X-rays (Crab-type) from secondary $e^\pm$ pairs (Cheng, Ho & Ruderman 1986a, 1986b; Ho 1989; Chiang & Romani 1992; Cheng & Ding 1994; Cheng & Wei 1995; Romani 1996). Recently, Zhang & Cheng (1997) have proposed a self-consistent model for "thick" outer gaps for the high energy emission from mature pulsars such as Geminga. In their model, the gap size depends on the properties of the pulsar and the observed γ-rays can be produced by synchro-curvature radiation of primary $e^\pm$ pairs (Cheng & Zhang 1996). In Table 2, the characteristic ages of all the γ-ray pulsar candidates are greater than 10^4 years, these pulsars may have the Vela-type gaps, whose quantitative definition will be given in next section. It has been proposed that the thin outer gap model can explain the high energy radiation from Vela-type pulsars (e.g. Cheng & Ding 1994). Therefore, we will apply our thick outer gap model (Zhang & Cheng 1997) to all γ-ray pulsar candidates and the thin outer gap model given by Cheng & Ding (1994), in addition to the Vela-type pulsars. We describe these models briefly as follows.

3.1. *The thin outer gap model*

In the thin outer gap model, Cheng & Ding (1994) investigated the evolution of the γ-ray spectra of Vela-type pulsars with dif-

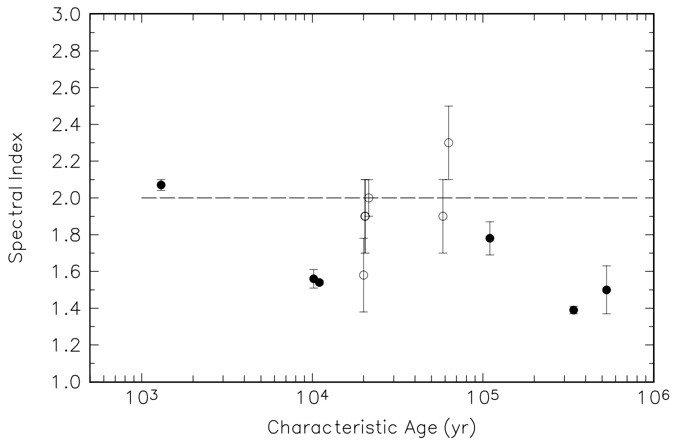

Fig. 1. Comparison of spectral indices of known γ-ray pulsars with those of the possible γ-ray pulsars. Solid circles represent the spectral indices of the known γ-ray pulsars (Nolan et al 1996) and empty circles represent the spectral indices of the possible γ-ray pulsars, 2EG J0008+7307 is taken from Brazier et al (1997) and the others are taken from Merck et al (1996).

ferent inclination angles and gave the period range for such pulsars. Following CHR II, they argued that the size (f which is defined as the ratio between the outer gap volume and R_L^3, and R_L is the light cylinder radius) of the outer gap for the Vela-type pulsar is constant and showed that the γ-ray spectrum from the thin outer gap should be given by

$$F_\gamma(E_\gamma) \propto \frac{1}{E_\gamma}\int_{\gamma_{min}}^{\gamma_{max}} d\gamma\gamma^{-2}\ln\left(\frac{\gamma_{max}}{\gamma}\right)F(y) \quad , \tag{2}$$

where, $y = E_\gamma/\hbar\gamma^2\omega_B$. Here γ_{max} and γ_{min} are the maximum and the minimum Lorentz factors of the secondary $e^\pm$ pairs given by

$$\gamma_{max} \sim \frac{mc^2}{E_{IR}} \sim mc^2\frac{\omega_B^3(r)}{\hbar}\left(\frac{mc^2\Omega}{e^2}\right)^{-2} \quad , \tag{3}$$

$$\gamma_{min} \sim \frac{\Omega mc^3}{e^2\omega_B^2(r)\sin^2\theta} \quad , \tag{4}$$

where $\Omega = 2\pi/P$, E_{IR} is a typical energy of IR photons, $\omega_B = (eB(r)/mc)$, $B(r) = B_s R^3/r^3$ for a dipole field, r is the typical distance to the outer gap, R is the stellar radius, and θ is the mean pitch angle of the secondary pairs with respect to the local magnetic field . They introduced a parameter $\alpha = r/R_L$ to characterize the mean distance to the thin outer gap. Following the arguments proposed by Ruderman & Cheng (1988), they showed that a Vela-type pulsar should then have a period which satisfies

$$P_t < P < P_c \tag{5}$$

where $P_t = 4.6\times10^{-2}B_{12}^{2/5}$, $P_c = 0.16B_{12}^{5/12}\alpha^{-5/4}sin^{1/6}\theta$ and P is in seconds. It should be noted that the normalization of Eq. (2) is determined by the fact that the γ-ray efficiency of the Vela-type outer gap defined by $\eta_\gamma = L_\gamma/I\Omega\dot{\Omega}$ is a constant in their model, so there are only two parameters (θ and α) in their model for calculating the spectrum. By fitting the γ-ray spectra of the Vela pulsar and PSR B1706-44, they found that $\sin\theta \sim 10^{-3}$. Here we will always assume $\sin\theta = 10^{-3}$, so there is only one parameter in the thin gap model. However, we would like to remark that such value of $\sin\theta$ may be too small for pulsars older than the Vela pulsar whose average mean free path should be larger than that of the Vela pulsar.

The size (f) of the Vela-type outer gap is assumed to be constant for parameters near those of Vela or $f \propto B_{12}^{-2/3}P^{5/3}$ for the Vela-type outer gap with Crab-type parameters (CHR II). The γ-ray efficiency for the Vela-type pulsar can then be expressed as

$$\eta_\gamma = \begin{cases} \eta(P, B_{12}) & \text{for} \quad P < P_t \\ \eta_{Vela} & \text{for} \quad P_t < P < P_c \end{cases} \quad , \tag{6}$$

where

$$\eta(P, B_{12}) = \eta_{Vela}\left(\frac{B_{12}}{3.37}\right)^{-2}\left(\frac{P}{0.089}\right)^5 \tag{7}$$

and η_{Vela} is the γ-ray efficiency of the Vela pulsar. According to Ruderman & Cheng (1988), the efficiency of the Vela-type pulsars will rapidly increase as P approaches P_c. We will assume that η_γ should be that from a thick outer gap model when $P \to P_c$. Details will be discussed in next section.

3.2. *The thick outer gap model*

In the thick outer gap model (Zhang & Cheng 1997), the size of the outer gap (f) is limited by pair production between the soft thermal X-rays from the stellar surface and the curvature photons with energy $E_\gamma(f)$ emitted by the primary electrons/positrons accelerated in the outer gap. The energy of the soft X-ray photons is determined by the backflow of the gap's electrons/positrons. Therefore the soft X-ray energy $E_X(f)$ is also a function of the gap size. Using $E_X(f)E_\gamma(f) \sim (mc^2)^2$, the size of the outer gap can be expressed as

$$f = 5.5P^{26/21}B_{12}^{-4/7} \quad . \tag{8}$$

The backflow primary electrons/positrons will radiate high energy photons and some of these photons will be converted into secondary pairs by magnetic pair creation. These secondary particles will immediately lose their energies via synchrotron radiation and then a cascade process may occur until the energy of the synchrotron photon is below 1 MeV when these photons come within a few stellar radii. Therefore, the expected X-ray spectrum for $E_X <$ MeV consists of soft thermal X-rays and hard non-thermal X-rays with spectral index ~ -2 and $L_X/\dot{E}_{sd} \sim 10^{-3}$ (see Zhang & Cheng (1997) and Cheng, Gil & Zhang (1997) for details).

Gamma-rays are produced inside the thick outer gap by synchro-curvature radiation from the primary $e^\pm$ pairs moving in spiral trajectory along the curved magnetic field lines. The primary $e^\pm$ pairs have an approximate power-law distribution inside the gap because the energy and density of the primary $e^\pm$ pairs depend on local values of magnetic field, electric field and radius of curvature. The radiation spectrum produced by the primary particles can then be expressed as (Zhang & Cheng 1997)

$$\frac{d^2N_\gamma}{dE_\gamma dt} \approx \frac{\dot{N}_0}{E_\gamma}\int_{x_{min}}^{x_{max}} x^{3/2}\frac{R_L}{r_c} \left[(1+\frac{1}{r_c^2Q_2^2})F(y) - (1-\frac{1}{r_c^2Q_2^2})yK_{2/3}\right]dx \quad (9)$$

where $\dot{N}_0 = \sqrt{3}e^2\gamma_0 N_0/hR_L$, $N_0 \approx 1.4\times10^{30}f(B_{12}/P)$ and $\gamma_0 \approx 2\times10^7 f^{1/2}(B_{12}/P)^{1/4}$;

$$r_c = xR_L/[(1+\frac{r_B}{R_L}\frac{1}{x})\cos^2\zeta + \frac{R_L}{r_B}x\sin^2\zeta] \ , \quad (10)$$

and

$$Q_2 = \frac{1}{xR_L}[(\frac{r_B}{R_L}\frac{1}{x}+1-3\frac{R_L}{r_B}x)\cos^4\zeta + 3\frac{R_L}{r_B}x\cos^2\zeta + (\frac{R_L}{r_B})^2x^2\sin^4\zeta] \ . \quad (11)$$

Here, $x = s/R_L$, s is the curvature radius of the magnetic field lines of the outer gap; x_{min} and x_{max} are minimum and maximum curvature radii in units of the radius of the light cylinder; $r_B = \gamma mc^2\sin\zeta/eB$, ζ is the steady state pitch angle of charged particle in the curved magnetic field and $\zeta \approx 0.79 f^{1/2}B_{12}^{-3/4}\ P^{7/4}x^{17/4}$; $F(y) = \int_y^\infty K_{5/3}(z)dz$, where $K_{5/3}$ and $K_{2/3}$ are the modified Bessel functions of order 5/3 and 2/3, and $y = E_\gamma/E_c$. The characteristic energy of the radiated photons is given by

$$E_c \approx 640.5\left(\frac{P}{B_{12}}\right)^{3/28} x^{-13/4}(R_LxQ_2)\ \text{MeV} \ . \quad (12)$$

The differential flux at the earth is given by

$$F(E_\gamma) = \frac{1}{\Delta\Omega d^2}\frac{d^2N_\gamma}{dE_\gamma dt} \ , \quad (13)$$

where $\Delta\Omega$ is the solid angle of γ-ray beaming and d is the distance to the pulsar. In this model, the three parameters, $\Delta\Omega$, x_{min} and x_{max}, depend on the detailed structure of the outer gap and the inclination angle of the pulsar.

In the thick outer gap model, the γ-ray luminosities are

$$L_\gamma \approx 3.6\times10^{31}f^3B_{12}^2P^{-4}\ \text{ergs s}^{-1} \ . \quad (14)$$

Because the average characteristic energy of the radiated photons can be approximated as $< E_c > \approx 10^{-3}(P/B_{12})^{3/28}$ ergs, the integrated flux for each pulsar,

$$F_\gamma^{th} = \frac{L_\gamma}{\Delta\Omega d^2 < E_c >} \approx 7\times10^{-7}\frac{1}{d_{kpc}^2\Delta\Omega}\left(\frac{B_{12}}{P}\right)^{11/28}\ \text{cm}^{-2}\ \text{s}^{-1} \ , \quad (15)$$

where d_{kpc} is the distance in units of kpc and $\Delta\Omega$ is in sr. Because of the uncertainty in the distance, the expected flux given by Eq. (15) is accordingly uncertainty. In Eq. (15), F_γ^{th} involves the solid angle $\Delta\Omega$. Generally, the solid angle varies with the pulsar. According to the analysis of Yadigaroglu & Romani (1995), the variation of solid angle can be up to one order of magnitude. Furthermore, our results from fitting the energy spectra of the known γ-ray pulsars indicate that the solid angle can be from ~ 0.5 to 2.5. Therefore, we believe that the solid angle may vary from ~ 0.3 to ~ 3.0. The conversion efficiency can be approximated by

$$\eta_\gamma(E_\gamma > 100MeV) \approx 1.7\times10^2B^{-12/7}P^{26/7} \ . \quad (16)$$

The above formula has been compared with the observed efficiencies of six known γ-ray pulsars and 350 pulsars whose ages range from 10^3 yr to 10^{10} yr with known γ-ray flux upper limits (Nel et al. 1996). Confirming results have been obtained (Zhang & Cheng 1998).

4. Comparison of model results with observed data

In this section, we compare our model results to the observed data about unidentified γ-ray sources. First, we estimate the size of the outer gap, f, for each pulsar. As mentioned above, the size of the outer gap is a constant in the thin outer gap models for the Vela-type pulsars and is a function of period and magnetic field in the thick outer gap model. A pulsar cannot have $f > 1$ in our model. We will first use Eq. (8) to determine the possible γ-ray pulsars. We find that the fractional sizes of all possible γ-ray pulsars except for that of PSR B1900+05 are less than unity. For PSR B1900+05, we have $f \approx 2$. Moreover, this pulsar ($P = 0.75$ s, $B_{12} = 3.1$, and characteristic age is 9.2×10^5 yr) is not a Vela-type pulsar according to Eq. (5). So we conclude that PSR B1900+05 is not a γ-ray pulsar, i.e. the observed high energy γ-ray radiation from 2EGS J1903+0529 should not come from the PSR B1900+05.

We now compare the calculated conversion efficiencies of spin-down power of possible γ-ray pulsars into γ-ray power with observed ones. According to Ruderman & Cheng (1988), the size of the outer gaps increase as the periods of pulsars increase. Therefore, the conversion efficiency will also increase with period for a given magnetic field. For the Vela-type pulsars, those whose periods satisfy Eq. (5), we estimate the conversion efficiency by using Eq. (6) and use Eq. (16) for mature pulsars. These conversion efficiencies for different magnetic fields are shown in Fig. 2. For comparison, the observed conversion efficiencies of possible γ-ray pulsars and known γ-ray pulsars are also shown, where a beaming solid angle of 1.0 steradian has been assumed.

Finally, we compare the calculated energy spectra with the observed spectra for the possible γ-ray pulsars in the thick outer gap model and for possible Vela-type pulsars in the thin outer gap model. In the thick outer gap model, we assume that the high energy γ-ray radiation from each of the six EGRET sources is completely from the corresponding possible γ-ray pulsars. We then estimate the expected flux by using Eq. (15) and set $F_\gamma^{ob} = F_\gamma^{th}$ to adjust for the beaming angle for each pulsar. Then, from the given period and magnetic field of each possible γ-ray pulsar, we can obtain the model spectrum using Eq. (10). In our

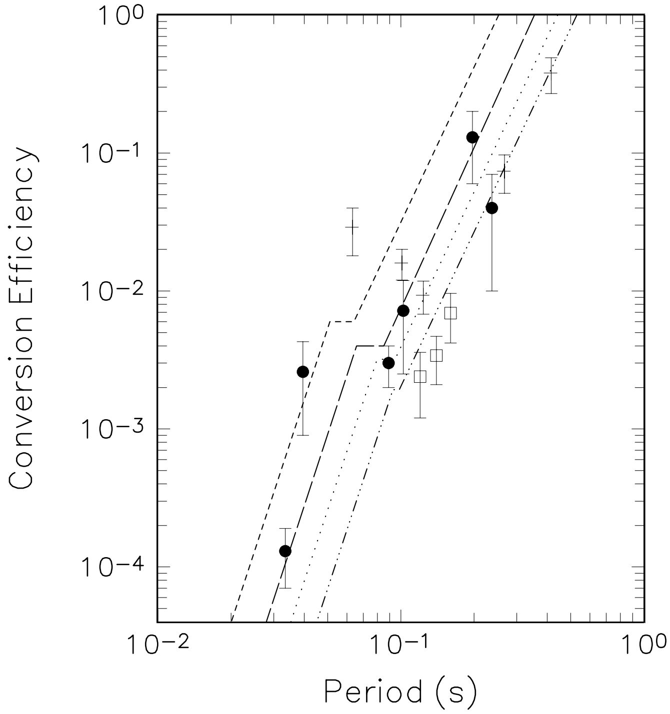

Fig. 2. γ-ray pulsar conversion efficiency versus pulsar period. The observed conversion efficiencies for the known γ-ray pulsars (solid circles) are taken from Nolan et al 1996. Plus symbols represent the conversion efficiencies of the possible γ-ray pulsars except for the possible γ-ray pulsar in SNR CTA 1. For the possible γ-ray pulsar in SNR CTA 1, the conversion efficiencies deduced by different values of P and B_{12} (see text) are labeled by the empty boxes. The expected results for $B_{12} = 1$, 2, 3.4 and 5 are shown by short-dashed, long-dashed, dotted and dot-dashed curves, respectively.

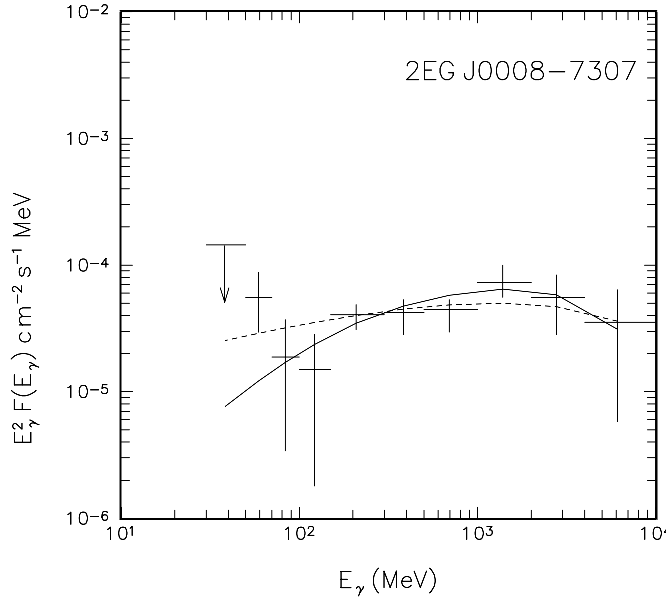

Fig. 3. The γ-ray energy spectrum of 2EG J0008+7307. The observed data are taken from Brazier et al (1997). The solid curve is the prediction of the thick outer gap model and the dashed curve is that from the thin outer gap model.

Table 3. Best-fit parameters for possible γ-ray pulsars.

Pulsar	Thin α	outer gap χ^2	Thick x_{min}	outer x_{max}	gap χ^2
CTA 1	0.54	5.1	0.68	2.1	4.8
B1046-58	0.59	2.5	0.75	2.2	5.2
B1758-23	0.264	7.3	0.58	2.1	10.5
B1823-13	0.63	4.9	0.6	2.3	10.6
B1853+01	0.38	7.3	0.55	2.2	9.3
J1105-6107	0.72	1.03	0.6	2.1	22.0

calculations, there are are two parameters: x_{min} and x_{max}. We choose these parameters to fit best the observed spectrum and use the χ^2 test to compare our model results with the observed results. In the χ^2 test, the upper limits of the observed energy spectrum for each object are not included. In the thin outer gap model for the Vela-type pulsars, expected spectra are calculated by using Eq. (2) with the normalized coefficient determined by equating the integrated flux to the observed flux. We fix $\sin\theta = 10^{-3}$ and change α to fit the observed spectra. The comparisons of two model results with the observed spectra for the possible γ-ray pulsars are shown in Figs. 3 to 8 and the best-fit parameters and χ^2 values are shown in Table 3.

Now, we describe our results for each possible γ-ray pulsars in detail as follows.

1.The possible γ-ray pulsar in *SNR CTA 1* - In the thick outer gap model, the expected fluxes in units of 10^{-8} cm^{-2} s^{-1} are 127 ± 54 for $P = 0.12$ and $B_{12} = 3.4$, 124.0 ± 53.0 for $P = 0.14$ and $B_{12} = 3.9$, and 127.8 ± 54.8 for $P = 0.16$ and $B_{12} = 4.6$ respectively. The uncertainty of the calculated flux is due to the distance uncertainty. These values are greater than the observed flux, which means and needs a beaming angle of about 2.7 ± 0.7 sr. Compared to the observed spectrum, our model results give $\chi^2 \approx 4.9$ for $P = 0.12$ s and $B_{12} = 3.4$, $\chi^2 \approx 4.8$ for $P = 0.14$ s and $B_{12} = 3.9$, and $\chi^2 \approx 4.6$ for $P = 0.16$ s and $B_{12} = 4.6$ respectively. In the thin outer gap model, the ratio of the observed conversion efficiency to Vela's conversion efficiency ($\eta_{Vela} \approx 0.4\%$) is $\sim 0.8 \pm 0.4$, and the best-fit for the observed spectrum gives $\chi^2 = 5.1$. Obviously both of these two models can explain the high energy γ-ray emission from this possible γ-ray pulsar. Therefore, we conclude that it is a possible γ-ray pulsar and the observed high energy γ-ray emission from 2EG J0008+7307 may come from it.

2.*PSR B1046-58* - This radio pulsar may be the counterpart of the 2EG J1049-5847. The beaming angle is $\sim 0.46 \pm 0.11$ and the best-fit gives $\chi^2 = 5.2$ in the thick outer gap model. In the thin outer gap model, the ratio of the observed conversion efficiency to Vela's conversion efficiency is $\sim 2.3 \pm 0.6$, and the best-fit for the observed spectrum gives $\chi^2 = 2.5$. From above results, we also conclude that PSR B1046-58 is a possible γ-ray pulsar.

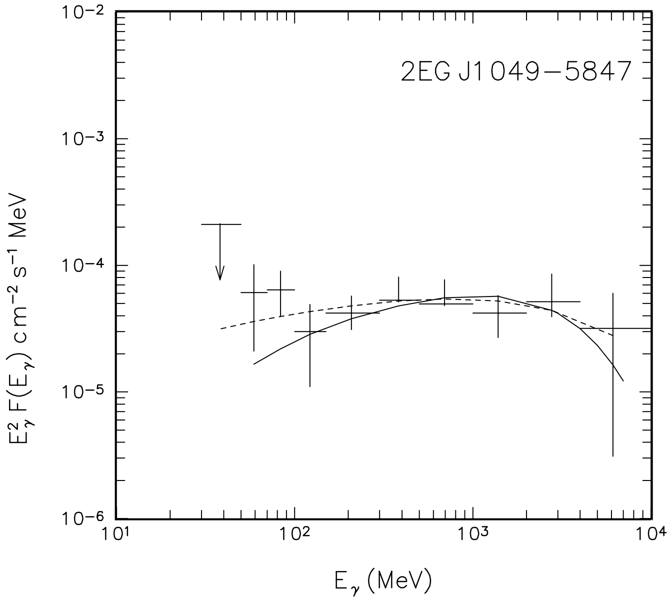

Fig. 4. The γ-ray energy spectrum of 2EG J1049-5847. The observed data are from Merck et al (1996). The solid curve and dashed curves represent results of the thick outer gap model and the thin outer gap model respectively.

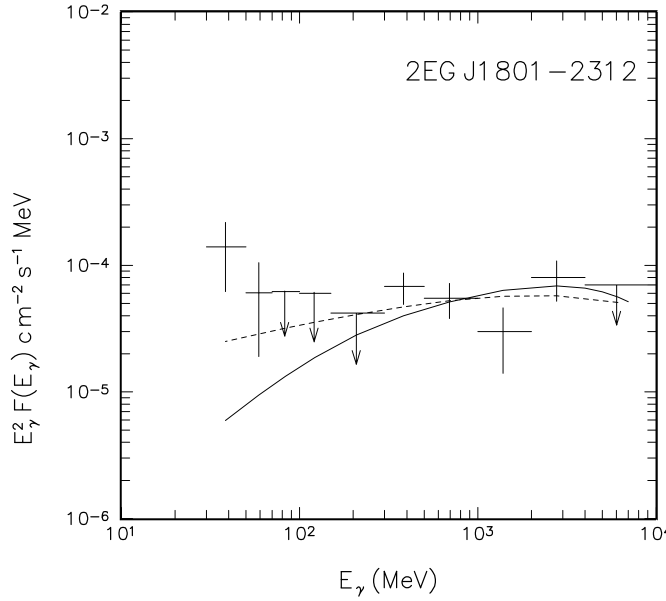

Fig. 5. The γ-ray energy spectrum of 2EG J1801-2312. The solid curve and dashed curves are the results from the thick outer gap model and the thin outer gap model respectively. The observed data are from Merck et al (1996).

3.*PSR B1758-23* - In the thick outer gap model, the needed beaming angel is $\sim 0.4 \pm 0.1$ and the χ^2 value is 10.5. Because 6 observed data are available, the χ^2 value per degree of freedom is about 2.6, which seems too large. On the other hand, in the thin outer gap model, although the value of χ^2 per degree of freedom is 1.5 for the best-fit, the ratio of the observed conversion efficiency to Vela's conversion efficiency is ~ 95, which is too large to be considered it as a Vela-type pulsar. Therefore, we cannot confirm that the high energy radiation from 2EG J1801-2312 is produced by PSR B1758-23.

4.*PSR B1823-13* - The beaming angle and the χ^2 value per degree of freedom (six observed data are available) are $\sim 0.23 \pm 0.07$ and ~ 2.6 respectively in the thick outer gap model. In the thin outer gap model, the the ratio of the observed conversion efficiency to Vela's conversion efficiency is ~ 4.0, and the χ^2 value per degree of freedom is ~ 1.0. Therefore, we suggest that the PSR B1823-13 may be a γ-ray pulsar.

5.*PSR B1853+01* - This radio pulsar is the overlapping counterpart of 2EG J1857+0118 (Yadigaroglu & Romani 1997). The beaming angle is $\sim 0.54 \pm 0.15$ and the χ^2 value per degree of freedom is ~ 1.9 (seven observed data are available). However, this radio pulsar is not a good Vela-type pulsar candidate because the observed conversion efficiency is ~ 15 times greater than that of Vela pulsar. Therefore, although the χ^2 value per degree of freedom is about 1.3 in the thin outer gap model, we do not conclude that this pulsar is a possible γ-ray pulsar which is observed by EGRET.

6.*PSR J1105-6107* - This is a new radio pulsar discovered by Kaspi et al (1997), which is the possible counterpart of 2EG J1103-6106. If we assume the high energy γ-ray radiation from 2EG J1103-6106 is produced by this young radio pulsar, then the

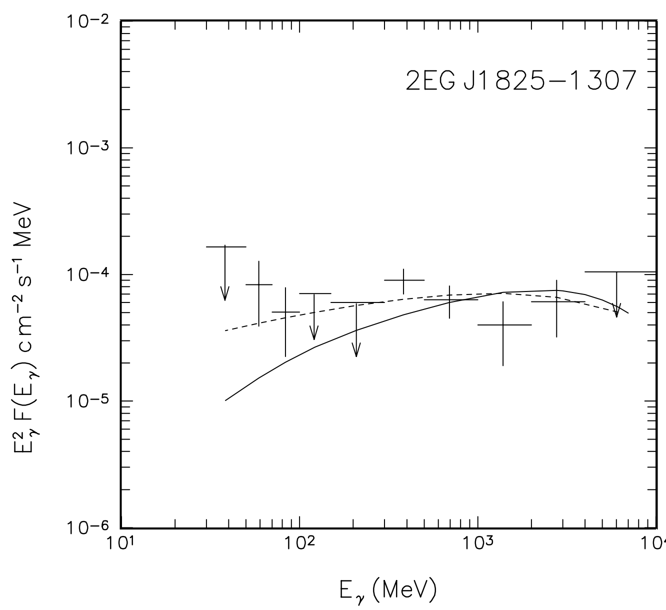

Fig. 6. The γ-ray energy spectrum of 2EG J1825-1307. The observed data are from Merck et al (1996). The solid curve and dashed curves are fits with the thick outer gap model and the thin outer gap model respectively.

beaming angle is ~ 0.07. This is too small to be acceptable and the best fit of χ^2 value per degree of freedom is 11 in the thick outer gap model. Furthermore, in the thin outer gap model, the observed efficiency is 7.3 times greater than that of Vela pulsar and its characteristic age is $\sim 6.3 \times 10^4$ yr. which seem high for Vela-type pulsars (cf. Fig. 2) although the best fit of χ^2 value per degree of freedom is 0.4. Therefore, we hesitate to suggest

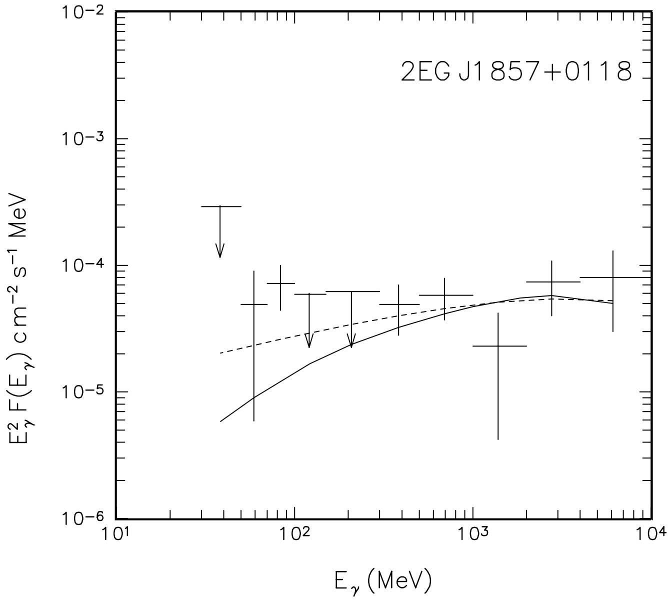

Fig. 7. The γ-ray energy spectrum of 2EG J1857+0118. The observed data are from Merck et al (1996). The solid curve and dashed curves are from the thick outer gap model and the thin outer gap model respectively.

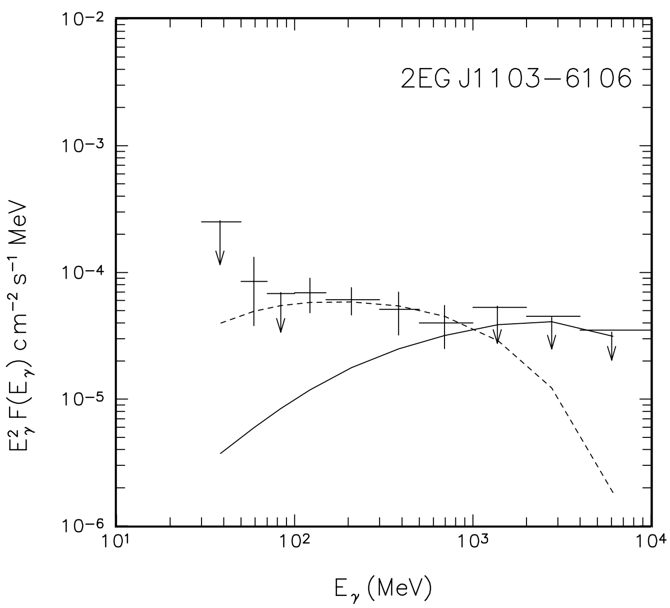

Fig. 8. The γ-ray energy spectrum of 2EG J1103-6106. The observed data are taken from Merck et al (1996). The solid curve and dashed curves are from the thick outer gap model and the thin outer gap model respectively.

that this radio pulsar is responsible for the high energy γ-ray radiation from 2EG J1103-6106.

5. Conclusions and discussions

It has been suggested that the counterparts of seven unidentified EGRET sources are probably pulsars (Kaaret & Cottam 1996; Yadigaroglu & Romani 1997). Assuming the high energy γ-ray radiation from these sources is produced by pulsars, we have considered the high energy radiations from these seven EGRET sources based on outer gap models (Cheng & Ding 1994; Zhang & Cheng 1997). We have calculated the conversion efficiency and energy spectra and χ^2 test has been performed for the spectral fit. Our results indicate that a possible γ-ray pulsar in supernova remnant CTA 1, proposed by Brazier et al (1997), and two radio pulsars PSR B1046-58 and PSR B1823-13, can produce the observed high energy γ-ray radiation from 2EG J0008-7307, 2EG J1049-5847 and 2EG J1825-1307 respectively; we conclude that these three EGRET sources are γ-ray pulsars. It should be noted that there is not yet convincing evidence for a γ-ray pulsar in SNR CTA 1. If it exists, we suggest that this pulsar should have a period of 0.12 - 0.16 s and a magnetic field of $(3. - 4.6) \times 10^{12}$ G. For 2EG J1801-2312, and 2EG J1857+0118, that their counterparts are PSR B1758-23 and PSR B1853+01 is doubtful.

For 2EG J1801-2312 and 2EG J1857+0118, counterparts are likely other young objects. Yadigaroglu & Romani (1997) pointed out that these two EGRET sources are probably associated with OB Sgr 1 C and SNR W44 respectively. Therefore, we believe that the high energy radiation from these three EGRET sources are probably composites of several counterparts. For these two EGRET sources the γ-ray emission could be a combination of the emission from γ-ray pulsars and cosmic interactions from density enhancements of ISM gas (corresponding to H II counterparts) or from local acceleration of cosmic rays by SNRs.

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