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Young pulsars and unidentified gamma-ray sources at the Galactic plane

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Abstract. We present a statistical study on possible association between the unidentified γ-ray point sources at the Galactic plane ($|b| \leq 5°$) and the Galactic young pulsars with ages of less than 10^6 yr. Based on the possible positional coincidence of the unidentified EGRET sources in the third catalog with the Galactic objects given by Romero et al. (1999) as well as the outer gap model of γ-ray pulsars proposed by Zhang & Cheng (1997), we have made a statistical analysis on whether most unidentified EGRET point sources in the Galactic plane have pulsar origin. In our analysis, we use an evolving γ-ray solid angle which is the function of pulsar's parameters such as period, magnetic field and magnetic inclination angle. The simulated distributions of the distance and γ-ray energy flux are compared to observed data using Kolmogorov-Smirnov (KS) test. Our results suggest that young pulsars may account for the majority of unidentified EGRET sources that are positionally associated with supernova remnants and OB star associations, in such a way that two thirds are young radio quiet pulsars and one third are young radio pulsars. We have studied the variability of these unidentified γ-ray sources and found that most of them may be non-variable. Furthermore, we expect that GLAST may detect $\sim 80\dot{N}_{100}$ radio pulsars and $\sim 1100\dot{N}_{100}$ unidentified γ-ray point sources in the Galactic plane with $|b| \leq 5°$, where $\dot{N}_{100}$ is the birth rate of neutron stars in units of 100 years. This model predicts that γ-ray point sources located at small distances are more than those predicted by a γ-ray pulsar model with a constant beaming solid angle.

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

1. Introduction

The third EGRET catalog (Hartman et al. 1999) lists 170 unidentified point sources, where 55 unidentified point sources are at low Galactic latitudes ($|b| < 5°$). Compared to the 96 unidentified EGRET sources (where 30 of them are at low Galactic latitudes ($|b| < 5°$)) listed in the second catalog and its supplement (2EG) (Thompson et al. 1995; Thompson et al. 1996), the sources in the current sample double in number those of the old one. Many authors have studied the possible associations of the unidentified γ-ray point sources with known objects. For example, Montmerle (1979) showed that about half of the 11 unidentified Galactic COS B sources are in regions with young objects such as supernova remnants and OB massive stars. Kaaret & Cottam (1996) analyzed the unidentified EGRET sources at $|b| < 5°$ listed in 2EG catalog (2EG sources) and found significant correlation between the positions of the unidentified 2EG sources and OB associations. They estimated distances to the unidentified γ-ray sources from the OB associations and luminosities, and verified that the distribution of luminosities for the unidentified γ-ray sources is consistent with that of known γ-ray pulsars. Yadigaroglu & Romani (1997) have made a similar study and searched the possible associations of the unidentified 2EG sources with OB associations, SNRs, young pulsars, HII regions and young open clusters. They have found that 23 unidentified γ-ray sources have their counterparts (so their distances can be estimated) and concluded that young pulsars can account for essentially all low latitude unidentified EGRET sources. Additionally, Yadigaroglu & Romani (1995) showed that most of the unidentified EGRET sources are expected to be radio-quiet pulsars with no detectable radio emission. Cheng & Zhang (1998) have obtained similar results as that of Yadigaroglu & Romani (1995) by using their self-consistent outer gap model proposed in Zhang & Cheng (1997).

Recently, Romero et al. (1999) have studied the possible associations of the unidentified EGRET sources listed in the third (3EG) catalog with Wolf-Rayet and Of stars, SNRs and OB associations (considered as pulsar tracers). They found that 6 unidentified γ-ray sources of the 3EG catalog are positionally coincident with WR stars, 4 with Of stars, 22 with SNRs and 26 with OB associations. Obviously, at present, the number of the counterparts of the unidentified γ-ray sources increases significantly, compared to that of Yadigaroglu & Romani (1997). In such case, are still most unidentified EGRET sources in the Galactic plane young pulsars or Geminga-like pulsars? Motivated by this question, we will use the outer gap model of γ-ray pulsars proposed by Zhang & Cheng (1997) to examine the population predictions in detail and compare the results with the observed unidentified γ-ray sources in the Galactic plane.

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Up to date, EGRET has detected pulsed γ-ray emission from at least six γ-ray pulsars (Crab, Vela, Geminga, PSR B1076-44, PSR B1951+32 and PSR B1055-52) with some evidence for a seventh, PSR B0656+14 (for a summary, for example, see Thompson et al. 1997) and for an eighth, PSR B0146-58 (Kaspi et al. 1999). There are two broad kinds of γ-ray pulsar models: polar gap models (Harding 1981; Daugherty & Harding 1994; Daugherty & Harding 1996; Dermer & Sturner 1994; Sturner & Dermer 1994; Sturner et al. 1995) and outer gap models (Cheng et al. 1986a; Cheng et al. 1986b; Ho 1989; Chiang & Romani 1992; Cheng & Ding 1994; Cheng & Wei 1995; Romani 1996; Zhang & Cheng 1997). Based on the models for γ-ray production, the detailed statistical properties of γ-ray pulsars have been studied by using Monte Carlo methods by many authors (Bailes & Kniffen 1992; Yadigaroglu & Romani 1995; Sturner & Dermer 1996; Cheng & Zhang 1998). Here, we will present the statistical analysis of the γ-ray properties of those unidentified EGRET sources which are associated with some known objects such as OB associations and SNRs based on the outer gap model proposed by Zhang & Cheng (1997) and the simulation procedure given by Cheng & Zhang (1998). In Sect. 2, we will review the observational data of the unidentified EGRET sources listed in the 3EG catalog and the possible counterparts. In Sect. 3, we describe briefly the outer gap model which we use and the Monte Carlo simulation of the Galactic pulsar population. In Sect. 4, we present the simulated results and compare them with the unidentified point sources of EGRET. Finally a brief summary and conclusions are given in Sect. 5.

2. Unidentified EGRET sources and possible counterparts

In the Galactic plane with $b \leq 10°$, there are 74 unidentified EGRET sources listed in third catalog (Hartman et al. 1999). In order to find their counterparts in the Galactic plane, Romero et al. (1999) have studied the level of two-dimensional positional coincidences between these EGRET sources and different populations of Galactic objects such as WR and Of stars, SNRs and OB associations (considered as pulsar tracers). They found that the counterparts of these EGRET sources are 6 WR stars, 4 Of stars, 22 SNRS and 26 OB associations and there is overwhelming statistical evidence for the association of the unidentified EGRET sources with SNRs and OB star forming region. From their analysis, we can see that (i) 39 unidentified EGRET sources have their counterparts, some of them more than one. For instance, 3EG 1102-6103 is positionally consistent with WR 39, SNR G290.1-0.8 and the OB association Car 2. And (ii) the Galactic latitudes of these 39 unidentified EGRET sources are within $b \leq 5°$. In Table 1, we list the 38 unidentified EGRET sources listed in 3EG catalog and possible counterparts which are given by Romero et al. (1999). For these unidentified EGRET sources, their names, Galactic longitudes and latitudes, fluxes and spectral indexes have been given, with the only exception is 3EG J1746-2851, whose spectral index is not determined. When we estimate its γ-ray energy flux, we will assume that the spectral index is 2.0.

Furthermore, we would like to briefly discuss these counterparts. Romero et al. (1999) found out that 6 WR stars and 4 Of stars are possible counterparts of the unidentified EGRET sources. These stars are massive stars with strong winds. There are several mechanisms of producing γ-rays in such massive stars (e.g. Chen & White 1991; White & Chen 1992). Obviously, the γ-ray production in these massive stars is different from that in pulsars. Moreover, in 9 of these counterparts, the corresponding unidentified EGRET sources also have other counterparts such as SNRs and OB associations. So we do not consider these massive stars in our following analysis because we are focusing on the possible association of the unidentified EGRET sources with the objects related to pulsars.

It is generally believed that the neutron stars are formed in supernova explosion. After such an explosion, a gaseous remnant and a pulsar are expected to be formed. As time goes by, the pulsar may move away from the supernova remnant because its kick velocity is very high: the mean value of the velocity is nearly 500 km s^{-1} (Lorimer et al. 1995; Lorimer et al. 1997), and the maximum velocity up to $\sim$ 2000 km s^{-1}. Therefore, old pulsars generally do not associate with their supernova remnant. The ages of the supernova remnants associated with pulsars are believed to be not larger than $\sim 10^6$ years (Gaensler & Johnston 1995). The question is why not all young pulsars associate with their supernova remnants. At present, more than 200 SNRs (Green 1998) and more than 800 radio pulsars have been detected. However, only 15 - 18 young pulsars have been found to associate with their supernova remnants (Gorham et al. 1996; Manchester 1998). Spruit & Phinney (1998) have suggested that neutron stars receive both their velocities and their rotational kinetic energies from unspecified natal kicks and concluded that many neutron stars will be born spinning too slowly to be observable. Moreover, for young pulsars, only some fraction of the population can be seen because of their radio beams. In fact, Tauris & Manchester (1998) found a beaming fraction of 30–40% for the pulsars with characteristic ages $< 3 \times 10^4$ yr by studying a large of polarization data of the pulsars. Therefore it cannot be ruled out that some young SNRs host neutron stars are still undetected because of their weak radio emission or their beaming effect. In Table 1, 5 SNRs which are the counterparts of the unidentified EGRET sources may associate with radio pulsars: G180.0-1.7 (PSR J0538+2817), G263.9-3.3 (PSR B0835-45), G290.1-0.8 (PSR J1105-6107), G6.4-0.1 (PSR B1758-23) and G34.7-0.4 (PSR B1853+01). So we believe that some SNRs associate with pulsars and include SNRs counterparts in our analysis.

For OB associations, they are considered as pulsar tracers. Pulsars which are born within an OB association and have low proper motions will be near their parent OB associations. If the transverse speed of a pulsar with an age of 10^5 yr at a distance of 1.5 kpc is 250 km s^{-1}, then it moves 1° from its point of origin. Using the 2EG catalog and the OB associations in the catalog by Mel'nik & Efremov (1995), Kaaret & Cottam (1996) have found that 9 of unidentified EGRET sources listed in the 2EG catalog

Table 1. Unidentified γ-ray point sources whose positions are coincident with OB associations and SNRs.

Name (3EG J)	l (deg)	b (deg)	F_γ [a]	α	r (kpc) OB	r (kpc) SNR	Age(yr) [b] SNR	I_i [d]
0229+6151	134.20	1.15	37.9±6.2	2.29±0.18	2.01	...	...	0.48±0.34
0542+2610	182.02	-1.99	14.7±3.2	2.67±0.22	...	1.80[(1)]	$\sim 10^5$	1.17±0.83
0617+2238	189.00	3.05	51.4±3.5	2.01±0.06	1.34	1.50[(2)]	$6 \cdot 10^3$	0.62±0.40
0631+0642	204.71	-1.30	14.2±3.4	2.06±0.15	...	1.20[(3)]	$(3-15) \cdot 10^4$	2.00±1.43
0634+0521	206.18	-1.41	15.0±3.5	2.03±0.26	1.48	1.20[(3)]	$4 \cdot 10^4$	0.49±0.35
0824-4610	263.28	-4.89	63.9±7.4	2.36±0.07	0.49	0.50[(4)]	$1.1 \cdot 10^4$	1.10±0.78
0827-4247	260.84	-2.46	42.6±7.4	2.10±0.12	...	2.00[(5)]	$3.7 \cdot 10^3$	0.45±0.31
0841-4356	263.29	-1.10	47.5±9.3	2.15±0.09	...	0.50[(4)]	$1.2 \cdot 10^4$	1.15±0.82
0848-4429	264.50	-0.46	20.1±7.7	2.05±0.16	1.41	...	...	1.04±0.74
1013-5915	283.93	-2.34	33.4±6.0	2.32±0.13	...	3.80[(2)]	10^4	0.45±0.32
1027-5817	284.94	-0.52	65.9±7.0	1.94±0.09	2.14	...	...	0.53±0.38
1048-5840	287.53	0.47	61.8±6.7	1.97±0.09	2.64	...	...	0.36±0.26
1102-6103	290.12	-0.92	32.5±6.2	2.47±0.21	2.16	1.90[(2)]	$6.3 \cdot 10^4$	0.72±0.51
1308-6112	305.01	1.59	22.0±6.1	3.14±0.59	1.76	...	...	0.80±0.57
1410-6147	312.18	-0.35	64.2±8.8	2.12±0.14	1.51	1.90[(2)]	$1.5 \cdot 10^4$	0.44±0.31
1420-6038	313.63	0.37	44.7±8.6	2.02±0.14	1.51	...	...	0.85±0.61
1639-4702	337.75	-0.15	53.2±8.7	2.50±0.18	1.59	12.3[(6)]	$\sim 10^5$ [c]	0.76±0.54
1655-4554	340.48	-1.61	38.5±7.7	2.19±0.24	1.35	...	...	0.47±0.34
1714-3857	348.04	-0.09	43.6±6.5	2.30±0.20	...	7.5[(4)]	$\sim 8 \cdot 10^3$ [c]	0.73±0.52
1718-3313	353.20	2.56	18.7±5.1	2.59±0.21	1.23	...	...	0.97±0.70
1734-3232	355.64	0.15	40.3±6.7		1.31	~ 2.7	$\sim 3 \cdot 10^4$ [c]	0.97±0.70
1744-3011	358.85	-0.52	63.9±7.1	2.17±0.08	...	2.6[(2)]	$9.7 \cdot 10^3$	0.72±0.51
1746-2851	0.11	-0.04	119.9±7.4	1.70±0.07	...	8.5	$10^4 - 10^5$	0.71±0.51
1800-2338	6.25	-0.18	61.3±6.7	2.10±0.10	...	3.0[(2)]	$5.8 \cdot 10^4$	0.60±0.43
1809-2328	7.47	-1.99	41.7±5.6	2.06±0.08	1.94	...	...	0.96±0.69
1823-1314	17.94	0.14	42.0±7.4	2.69±0.19	1.48	...	...	1.15±0.82
1824-1514	16.37	-1.16	35.2±6.5	2.19±0.18	1.48	~ 2.4	$\sim 5 \cdot 10^5$ [c]	1.10±0.78
1826-1302	18.47	-0.44	46.3±7.3	2.00±0.11	1.48	...	...	1.04±0.74
1837-0423	27.44	1.06	19.1	2.71±0.44	...	2.0[(8)]	$\sim 3.5 \cdot 10^4$	3.58±2.55
1856+0114	34.60	-0.54	67.5±8.6	1.93±0.10	...	3.0[(3)]	10^4	1.10±0.79
1903+0550	39.52	-0.05	62.1±8.9	2.38±0.17	...	5.5[(3)]	10^3	0.85±0.61
2016+3657	74.76	0.98	34.7±5.7	2.09±0.11	1.17	12.0[(3)]	$\sim 6 \cdot 10^3$	0.85±0.61
2020+4017	78.05	2.08	123.7±6.7	2.08±0.04	1.17	1.5[(2)]	10^4	0.39±0.28
2021+3716	75.58	0.33	59.1±6.2	1.86±0.10	1.17	...	...	0.87±0.62
2022+4317	80.63	3.62	24.7±5.2	2.31±0.19	1.17	...	...	0.87±0.62
2027+3429	74.08	-2.36	25.9±4.7	2.28±0.15	1.17	...	...	1.90±1.36
2033+4118	80.27	0.73	73.0±6.7	1.96±0.10	1.17	...	...	0.50±0.36
2227+6122	106.53	3.18	41.3±6.1	2.24±0.14	0.77	...	...	1.26±0.90

[a] F_γ is in units of 10^{-8} cm^{-2} s^{-1}.
[b] the estimated ages of SNRs.
[c] we use the formula given by Leahy & Wu (1989).
[d] I_i is the ratio of the fluctuation index of ith unidentified source to mean fluctuation index of known γ-ray pulsars (see text).
References: [(1)] Anderson et al. 1996; [(2)] Yadigaroglu & Romani, 1997; [(3)] Biggs & Lyne 1996; [(4)] Green 1984; [(5)] Pavlov et al. 1999; [(6)] Koralesky et al. 1998; [(7)] Leahy 1989; [(8)] Reich et al. 1984.

have position contours overlapping an OB association and other 7 lie within 1° angular distance. They estimated that the fraction of pulsars with ages less than 10^5 yr found within 1° of OB associations should be 0.25–0.4. Although none of six known γ-ray pulsars are coincident with any OB associations, there are strong evidence that part of the pulsar population comes from OB associations. Recently, Romero et al. (1999) have studied the association between unidentified EGRET sources listed in the 3EG catalog and OB associations. They found that 26 OB associations are the counterparts of the unidentified EGRET sources, 8 out of 26 OB associations are possible pulsar candidates, which is consistent with prediction of Kaaret & Cottam (1996). The mean angular separation between the centroid of the OB association and the unidentified EGRET source is 1.5° although most sources are at angular distance of less than 1°.

As mentioned above, both SNRs and OB associations may contain pulsars, some of these pulsars have been detected at radio band and/or X-ray energy range, others may have weak radio emission so that they have not been detected or do not exist in the SNRs and OB associations. However, at least some of SNRs and OB associations should associate with the pulsars, so we will focus on them as counterparts of unidentified EGRET sources. Therefore, we have a sample which have 38 SNRs and OB associations. Because an unidentified EGRET source in Table 1 may be coincident with both an OB association and a SNR, we consider two possible cases of the observed sample

Case 1: we assume that the observed sample consists of 26 OB associations and 12 SNRs. In this case, the OB associations which are the counterparts of the unidentified EGRET sources are selected first and then SNRs are selected.

Case 2: we assume that the observed sample is composed of 22 SNRs and 16 OB associations, which means that SNRs are selected first.

3. The model and Monte Carlo simulations

In this section, we will describe our Monte Carlo simulation. At present, the six known γ-ray pulsars have their ages of less than 10^6 yr, and the pulsars in the SNRs and OB associations which are the counterparts of the unidentified EGRET sources have also ages less than of 10^6 yr. Therefore, we assume that the maximum age is 10^6 yr in our simulations. The assumed initial values of the parameters of pulsars at birth including the distributions of initial period, position, velocity and magnetic field are based on the statistical results of observed radio pulsars (see Cheng & Zhang (1998) for details).

3.1. Main assumptions and radio pulsar population

We use the following assumptions for generating the Galactic pulsar population:

(i) The pulsars are born at a rate ($\dot{N}_{NS} \sim (1-2)$ per century) with spin periods of $P_0 = 30$ ms.

(ii) The initial position for each pulsar is estimated from the distributions $\rho_z(z) = (1/z_{\rm exp})\exp(-|{\rm z}|/{\rm z}_{\rm exp})$ and $\rho_R(R) = (a_R/R^2_{\rm exp})R\ \exp(-{\rm R}/{\rm R}_{\rm exp})$, where z is the distance from the Galactic plane, R is the distance from the Galactic center, $z_{exp} = 75$ pc, $a_R = [1-e^{-R_{\rm max}/R_{\rm exp}}(1+R_{\rm max}/R_{\rm exp})]^{-1}$, $R_{\rm exp} = 4.5$ kpc and $R_{\rm max} = 20$ kpc (Paczynski 1990; Sturner & Dermer 1996).

(iii) The initial magnetic fields are distributed as a Gaussian in log B with mean log B_0=12.4 and dispersion $\sigma_B = 0.3$. We ignore any field decay for these rotation-powered pulsars.

(iv) The initial velocity of each pulsar is the vector sum of the circular rotation velocity at the birth location and a random velocity from the supernova explosion (Paczynski 1990; Cheng & Zhang 1998), the circular velocity is determined by Galactic gravitational potential and the random velocity are distributed as a Maxwellian distribution with dispersion of three dimensional velocity $\sigma_V = \sqrt{3} \times 100\,{\rm km\,s^{-1}}$ (Lorimer et al. 1997).

Once the initial properties of a pulsar at birth are given, the pulsar period at time t can be estimated by

$$P(t) = \left[P_0^2 + \left(\frac{16\pi^2 R_{NS}^6 B^2}{3Ic^3}\right)t\right]^{1/2} , \quad (1)$$

where, R_{NS} is the neutron star radius and I is the neutron star moment of inertia. The period derivative ($\dot{P}$) can be determined by

$$P\dot{P} = (8\pi^2 R_{NS}^6/3Ic^3)B^2 . \quad (2)$$

Furthermore, the pulsar position at time t is determined following its motion in the Galactic gravitational potential. Using the equations given by Paczynski (1990) for given initial velocity, the orbit integrations are performed by using the 4th order Runge Kutta method with variable time step (Press et al. 1992) on the variables R, V_R, z, V_Z and ϕ. Then the sky position and the distance of the simulated pulsar can be calculated.

In order to generate a pulsar population detectable at the radio band, we need to consider radio selection effects: the pulsar must satisfy that its radio flux is greater than the radio survey flux threshold and its broadened pulse width is less than the rotation period (e.g. Sturner & Dermer 1996). Briefly, the minimum detectable average flux density, $S_{\rm min}$, of a pulsar's survey depends mainly on receiver and sky background noise temperatures, the broadened pulse width, pulsar's period etc. The pulsar which satisfies

$$L_{400}/d^2 \geq S_{\rm min} \quad (3)$$

is considered to be a radio-detectable pulsar, where L_{400} is the radio luminosity at 400 MHz and d is the distance to the pulsar. The radio beaming fraction can be expressed as (Emmering & Chevalier 1989)

$$f_r(\omega) = (1-\cos\omega) + (\pi/2-\omega)\sin\omega , \quad (4)$$

where a random distribution of magnetic inclination angles is assumed and ω is the half-angle of the radio emission cone. Here we will use the model of Lyne & Manchester (1988) corrected by Biggs (1990), i.e. $\omega = 6^\circ.2 \times P^{-1/2}$. Then, following Emmering & Chevalier (1989), a sample pulsar with a given period P is chosen in one out of $f_r(P)^{-1}$ cases using the Monte Carlo method.

3.2. Gamma-ray emission and gamma-ray detectability

We use the γ-ray pulsar model given by Zhang & Cheng (1997) to describe the high energy γ-ray emission from the rotation-powered pulsars. In this model, the characteristic photon energy is completely determined by the fractional size of the outer gap (f_s) and is given by $E_\gamma(f_s) \approx 2 \times 10^8 f_s^{3/2} B_{12}^{3/4} P^{-7/4}$ eV, where P is the pulsar period in units of seconds, B_{12} is the dipolar magnetic field in units of 10^{12} G and the radius of the neutron star (R) is assumed to be 10^6 cm. The fractional size of the outer gap (f_s) is limited by the pair production between the soft thermal X-rays from the stellar surface and the synchro-curvature photons with energy $E_\gamma(f_s)$ 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 primary electrons/positrons. Half of the primary $e^\pm$ pairs in the outer gap will move toward the star and lose their energy via the curvature radiation. Although most of the energy of the primary particles will be lost on the way to the star via curvature radiation, about $10.6P^{1/3}$ ergs per particle will still remain and will finally be deposited on the stellar surface. This energy will be emitted in terms of X-rays from the stellar surface (Halpern & Ruderman 1993). The characteristic energy of X-rays is given by $E_X^h \approx 3kT \approx 1.2\times10^3 P^{-1/6} B_{12}^{1/4}$ eV. The KeV X-rays from a hot polar cap will be reflected back to the stellar surface due to the cyclotron resonance scattering if there is large density of magnetic produced $e^\pm$ pairs near the neutron star surface (Halpern & Ruderman 1993), and eventually re-emitted as softer thermal X-rays with characteristic energy $E_X^s \approx 0.1 f_s^{1/4} P^{-1/4} E_X^h$. This means that the soft X-ray energy $E_X(f_s)$ is also a function of the gap size. Although the original X-ray photon density is low, every pair resulting from X-ray and curvature photon interactions can emit $\sim 10^5$ photons in the outer gap. Such a large multiplicity can produce a sufficient numbers of $e^\pm$ pairs as to sustain the outer gap. From the condition for the photon-photon pair production, the fractional size of the outer gap, which is the ratio of the average vertical separation of the outer gap boundaries in the plane of ($\mathbf{\Omega}$, μ) to the radius of the light cylinder, can be determined as

$$f_s \approx 5.5 \cdot P^{26/21} B_{12}^{-4/7} \quad . \tag{5}$$

It should be emphasized that $f_s \le 1$. If $f_s > 1$, it means that there is not sufficient $e^\pm$ pairs near the neutron star surface and then the KeV X-rays from a hot polar cap will escape from the star. Gamma-rays are produced inside the outer gap by synchro-curvature radiation of the primary $e^\pm$ pairs (for details see Zhang & Cheng 1997). The expected γ-ray luminosities can be expressed as (Zhang & Cheng 1997)

$$L_\gamma \approx 3.6\times10^{31} f^3 B_{12}^2 P^{-4} \ \text{ergs s}^{-1} \quad . \tag{6}$$

It has been shown that Eq. (6) is a good approximation of the γ-ray luminosity with energy greater than 100 MeV of γ-ray pulsars (Zhang & Cheng 1998). Therefore, the energy flux of γ-rays with energy greater than 100 MeV can be expressed as

$$S_\gamma^{th}(E_\gamma > 100\text{MeV}) = \frac{1}{\Delta\Omega_\gamma d^2} L_\gamma(>100\text{MeV}) \quad . \tag{7}$$

where $\Delta\Omega_\gamma$ is the solid angle into which the pulsar radiation is beamed and d is the distance to the pulsar.

The beaming solid angle is not well known. In our previous statistical study of γ-ray pulsars (Cheng & Zhang 1998), we have used constant solid angle which is certainly oversimplified. In our recent three dimensional outer gap model (Cheng et al. 1999), however, the solid angle should be the function of the fractional size of the outer gap. According to the outer gap model, the γ-ray beam is very different from the radio beam. Generally, the γ-ray beam depends on the thickness of the outer gap. In the early three dimensional study of the pulsar magnetosphere (Romani & Yadigaroglu 1995; Yadigaroglu & Romani 1995; Romani 1996), the γ-ray beaming evolution has been studied. Yadigaroglu & Romani (1995) have estimated the beaming fraction of γ-ray pulsars and candidates; they found that the beaming fraction will become small as the pulsar's age increases although magnetic inclination angle of the pulsar has also played an important role. Assuming the magnetic inclination angles of all pulsars are $60°$, they found that the detection fraction should be ~ 80%, ~ 60% and ~ 25% for pulsars with ages of $\sim 10^3$ yr, $\sim 10^4$ yr and $\sim 10^5$–10^6 yr. Moreover, Romani (1996) has introduced a fractional width (w') which is defined by the ratio of the polar angle of the gap upper surface to the light-cylinder polar angle and expressed that the beaming fraction as the function of the magnetic inclination angle and the fraction width (w') (Eq. (15) in his paper). In the outer gap model of Zhang & Cheng (1997), the average fractional width (f_s) depends on the period and the magnetic field of the pulsar. Recently, we have used the three dimensional magnetosphere to study the three dimensional structure of outer gaps and the γ-ray morphologies (Cheng et al. 1999). The γ-ray beaming fraction can be approximated as

$$f_\gamma \sim \left(\frac{\alpha}{90°}\right)^a \frac{(1-b\cdot f_s)}{(1+b\cdot f_s)} \quad , \tag{8}$$

where α is the magnetic inclination angle of the pulsar, $a \sim 0.5$ and $b \sim 0.5$. Parameter a indicates the dependence of the beaming fraction on the magnetic inclination. Parameter b indicates an approximate position of the emission region in units of radius of the light cylinder. Small (large) b means that the emission is mainly produced near (far away from) the first open field line in the outer gap. It can be seen that the beaming fraction is determined if pulsar's parameters such as period, magnetic field and magnetic inclination are given. It should be pointed out that two outer gaps can exist in our model, which is different from the single pole outer gap model proposed by Romani & Yadigaroglu (1995).

We now consider the γ-ray selection effects. Generally, the γ-ray threshold varies over the sky. Yadigaroglu& Romani (1995) used a flux threshold of 3.0×10^{-10} erg cm^{-2} s^{-1}, which can be compared to the faintest 5 σ sources in the first EGRET Galactic plane source catalog (Fichtel et al. 1994), but Sturner & Dermer (1996) adopted 2×10^{-10} erg cm^{-2} s^{-1}, which is approximately equal to the flux observed from the γ-ray pulsar with the lowest flux, PSR B1951+32 (Ramanamurthy et al. 1995). However, in the third catalog, the faintest source in the catalog with significance $\sqrt{TS} \ge 4$ has a flux of $(6.2\pm1.7)\cdot10^{-8}$ cm^{-2} s^{-1} (Hartman et al. 1999). In our analysis, we include the criterion of likelihood $(TS)^{1/2}$ greater than 5 ($\sim 5\sigma$) when we choose the flux threshold. In Table 1, the statistical significances of 6 unidentified sources are less than 5. Here we will use

$$S_\gamma(>100\text{MeV}) \ge 1.2\times10^{-10} \ \text{erg cm}^{-2}\,\text{s}^{-1} \tag{9}$$

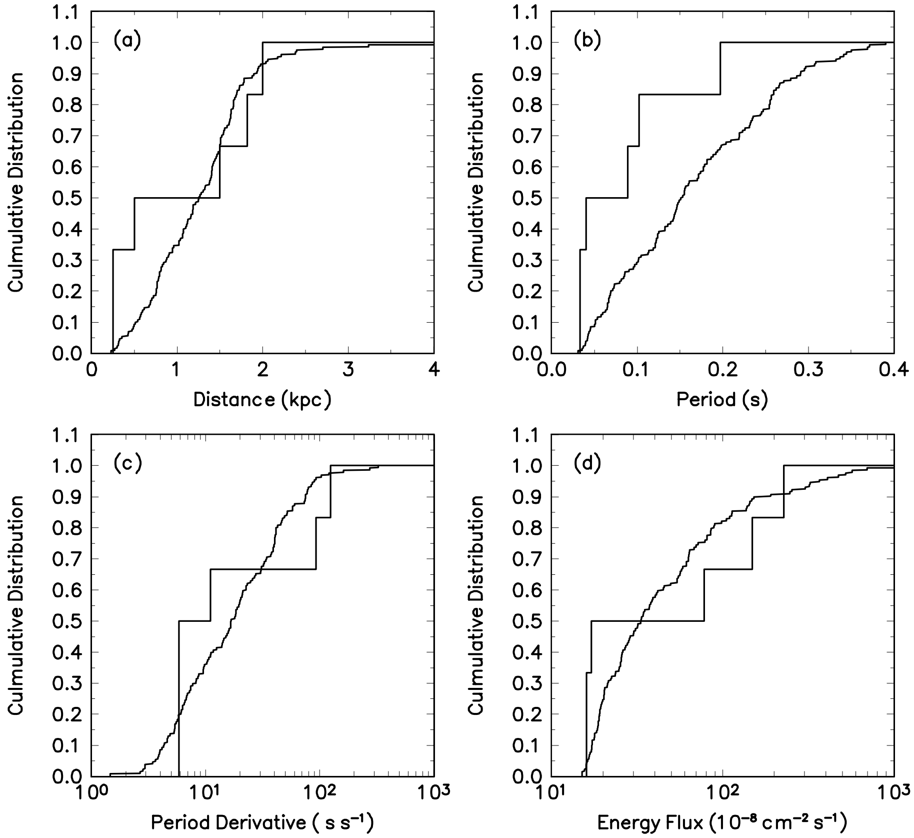


Fig. 1a–d. Comparisons of simulated distributions with the observed data of 6 known γ-ray pulsars. **a** distance, **b** period, **c** period derivative and **d** γ-ray energy flux.

as the minimum detectable γ-ray energy flux, which corresponds roughly to the faintest sources with $(TS)^{1/2} > 5$ in Table 1. In order to take γ-ray beaming effects into account, a sample γ-ray pulsar is chosen in one out of f_γ^{-1} cases using the Monte Carlo method. The pulsars which satisfy Eq. (9) and beaming condition will be detectable as γ-ray pulsars.

4. Simulations and results

Using the procedure of Monte Carlo simulations described by Cheng & Zhang (1998), we can produce a sample of γ-ray pulsar populations with ages of less than 10^6 yr and γ-ray energy fluxes above the minimum detectable (Eq. (9)). This simulated population consists of both radio pulsars (population I) and radio-quiet pulsars (population II). The details of the simulation procedure are described in Cheng & Zhang (1998). In order to model the pulsar populations, we generate pulsars with random ages of less than 10^6 yr with $\dot{N}_{100} = 1$. Initial period, position, magnetic field, and velocity of each pulsar are determined from known distributions. At time t, period and period derivative of a pulsar are calculated using Eqs. (1) and (2), and the pulsar position is estimated following the pulsar's motion in the Galactic gravitational potential. Then we can produce the total young γ-ray pulsar population which consists of young pulsars satisfying γ-ray selection effects, along with the relevant simulated quantities such as period, period derivative, and γ-ray energy flux. Galactic longitude and latitude of each simulated pulsar are recorded and the number of pulsars is labeled as N_γ. Adding radio selection effects and following the same simulation steps as those in generating total young γ-ray pulsar sample, we generate population I. In the population I, the pulsars must satisfy both radio selection and γ-ray selection conditions (the number of these pulsars in population I is represented by $N_{\gamma 1}$). In order to generate population II, we exclude the simulated pulsars in population I from the total young γ-ray pulsar population. In other words, the pulsars in population II satisfy the γ-ray selection condition but do not satisfy the radio selection condition. The number of the radio-quiet pulsars is approximated by $N_{\gamma 2} = N_\gamma - N_{\gamma 1}$. When comparing simulated results with observed results, the distances and γ-ray energy fluxes have been compared and the KS test has been made.

In our simulations, we compare first the simulated results (i.e. population I) with the observed data of 6 known γ-ray pulsars using the KS test. The maximum deviations of period, period derivative, distance and γ-ray energy flux distributions from the observed distributions are 0.36, 0.46, 0.38, and 0.40, respectively. It can be seen that three out of four of the cumulative distributions cannot be rejected at better than 80% confidence level and the second at better than 90% confidence level. Therefore, we conclude that our model may explain the statistical properties of the γ-ray pulsars. Fig. 1 shows the comparison of the simulated distributions of period, period derivative, distance and γ-ray energy flux with observed those of the 6 known γ-ray pulsars. The comparison of simulated period distribution with the observed one is not so good. From Fig. 1b, the number of simulated pulsars with longer periods is larger than that

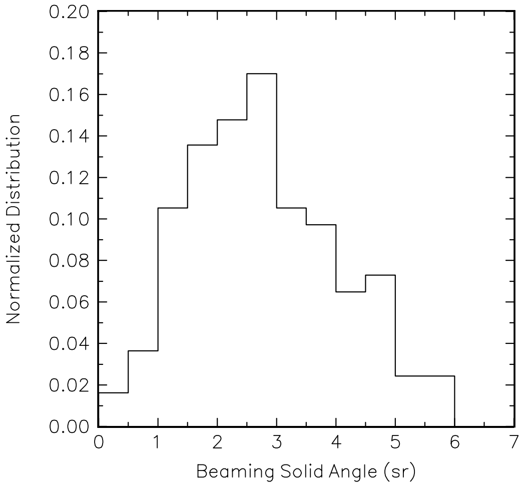


Fig. 2. The normalized distribution of the beaming solid angle for our simulated pulsars which should be detected in both radio and γ-ray energy regions. The EGRET γ-ray sensitivity (Eq. (9)) is used in our simulation.

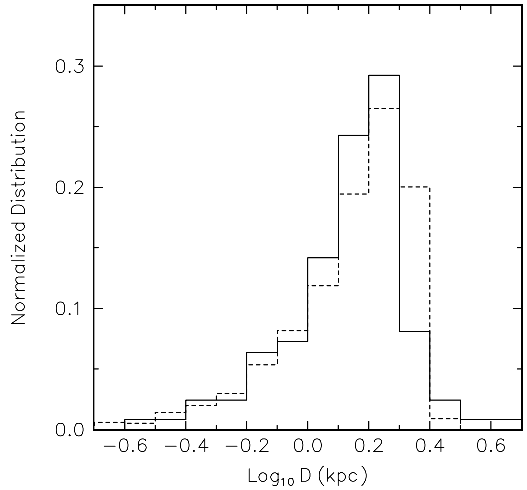


Fig. 3. The normalized distance distributions of the simulated young pulsars with an evolving beaming solid angle (solid histogram) and with a constant beaming solid angle (dashed histogram). The EGRET γ-ray sensitivity (Eq. (9)) is used in our simulation and the value 2.0 sr is used for constant beaming solid angle.

of the observed ones. However, our simulated result does not conflict with the observed data. The pulsars with longer periods will produce weaker fluxes. We expect that GLAST can confirm this result. It should be pointed out that we have used Eq. (8) to determine the beaming solid angles of the pulsars in our analysis. However, our previous analysis (Cheng & Zhang 1998) just used a constant beaming solid angle ($\Delta\Omega = 2.0$ sr) as a rough approximation. Fig. 2 shows the normalized distributions of the beaming solid angle for the simulated pulsars; the average value of the beaming solid angle is about 2.8 sr. In comparison with our previous results (Cheng & Zhang 1998), there are little changes for the distributions of period and period derivative of the simulated pulsars. There is, also, a moderate change in the distance distribution. We show the new distance distributions of the simulated young pulsars with an evolving beaming solid angle (solid histogram) and with a constant beaming solid angle (dashed histogram) in Fig. 3.

Furthermore, we use our model to consider the correlation between the unidentified EGRET sources and young pulsars. We assume that all unidentified EGRET sources which have counterparts consist of young pulsars, including radio pulsars and radio-quiet pulsars, so we perform Monte Carlo simulations to get a simulated sample: the total young γ-ray pulsar population. In order to compare the γ-ray energy fluxes of the simulated pulsars with the observed ones, we use the distance and the γ-ray energy flux as two independent variables and then examine the simulated results through the KS tests for these two variables against the observed values. The observed sample corresponds to case 1 described in Sect. 2, which consists of 26 OB associations and 12 SNRs. For such a sample, the hypothesis that the simulated pulsars and the observed unidentified EGRET sources were drawn from the same parent population cannot be rejected at the $> 80\%$ or $> 90\%$ confidence level if the maximum deviation from the observed data is < 0.170 or < 0.194. For the total young γ-ray pulsar population, the KS test indicates that the maximum deviation is 0.152 for the distance and 0.158 for the γ-ray energy flux. Furthermore, if we assume that the unidentified EGRET sources consist of the radio-quiet pulsars (population II), the KS test indicates that the maximum deviation is 0.153 for the distance and 0.169 for the γ-ray energy flux. The comparisons of the simulated results with the observed data are shown in Figs. 4a–b. From the above analysis, we find that the hypothesis that the simulated pulsars and the observed unidentified EGRET sources were drawn from the same population cannot be rejected at 80% confidence level for the total young γ-ray pulsar population and for population II.

We now compare the simulated samples with the other observed sample (i.e. case 2) which consists of 22 SNRs and 16 OB associations. In this sample, the distances of SNRs are taken from the literature except for G16.8-1.1 and G355.6+0.0. We have estimated the distances to these two SNRs from σ- D relationship using the equation given by Leahy & Wu (1989). The maximum deviations from the observed data for the distance and the γ-ray energy flux are 0.210 and 0.158 for population I and 0.174 and 0.169 for population II. In Fig. 5, we show the comparisons of the simulated distances of these two populations with the observed data. The comparisons of the simulated γ-ray energy fluxes with the observed data are the same as those in Fig. 4b. Therefore, for the observed sample of 38 unidentified 3EG sources positionally consistent with 22 SNRs and 16 OB associations (case I), we cannot conclude that the simulated pulsars and the observed unidentified EGRET sources were drawn from the same population.

From the above analysis, our results indicate that the distances of most simulated young pulsars are within 3 kpc, and the distributions of distances and γ-ray energy fluxes for both the simulated young and radio-quiet pulsars are consistent with those of the unidentified EGRET sources whose counterparts

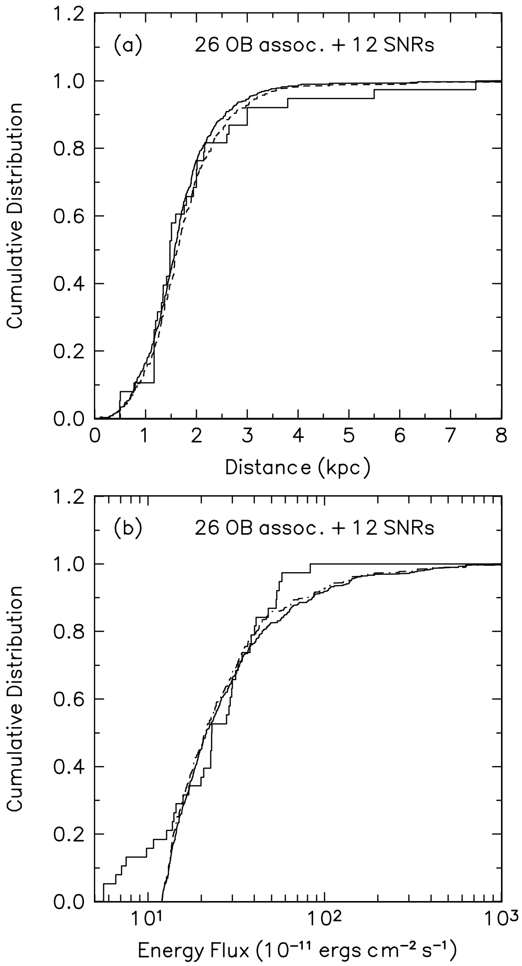


Fig. 4a and b. Comparisons of our model results with the observed data of unidentified EGRET sources which are spatially coincident with OB associations and SNRs (26 OB associations plus 12 SNRs). **a** Cumulative distribution of distance and **b** cumulative distribution of γ-ray energy flux. The histogram represents the observed data, the solid and dashed curves represent the simulated population I and II respectively.

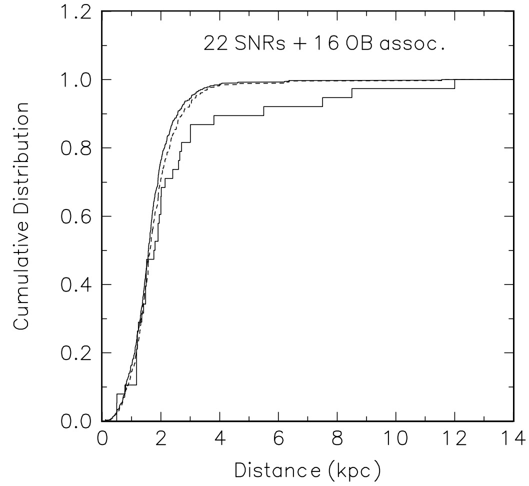


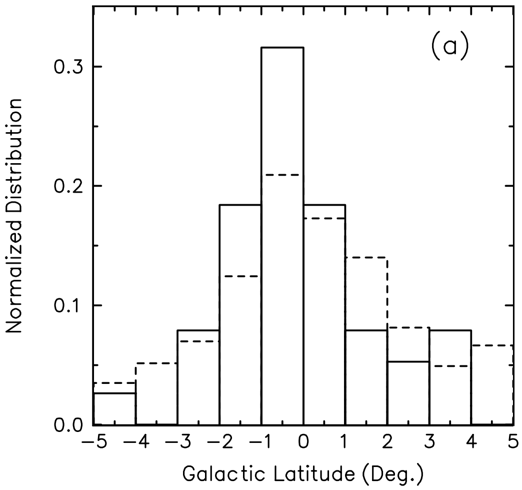
Fig. 5. Comparisons of our model distances with the observed data for 38 unidentified EGRET sources which are spatially coincident with 20 SNRs and 18 OB associations. The histogram represents the observed data, the solid and dashed curves represent the simulated population I and II respectively.

consist of 26 OB associations and 12 SNRs. Therefore, in this case, we have that a majority of the unidentified EGRET sources may be young pulsars. Our results are consistent with those of Yadigaroglu & Romani (1997). In fact, Yadigaroglu & Romani (1997) studied the associations of the massive stars in solar neighborhood (< 2.5 kpc) with the unidentified EGRET sources because their counterpart catalogs are incomplete beyond 2.5 kpc of the Sun. They found that the luminosity of the model population is consistent with that of the unidentified EGRET sources and concluded that young pulsars may explain essentially all of the excess low latitude unidentified EGRET sources.

Furthermore, we compare the Galactic distributions in latitude (b) and longitude (l) of those 38 unidentified EGRET sources (case 1) with the simulated young pulsars at $|b| \leq 5°$. The KS tests show that the maximum deviation is 0.165 for the distribution of Galactic latitude and 0.155 for the distribution of Galactic longitude. The results, consequently, indicate that the simulated results are consistent with the observed distributions in both longitude (l) and latitude (b). In Figs. 6a and b, we show the comparison of the observed differential normalized distributions with the simulated results, where the Galactic latitude is divided into 10 bins (each bin width is $1°$) and Galactic longitude into 8 bins (each bin width is $45°$).

From our simulation, our model predicts that there are $\sim 32\dot{N}_{100}$ young pulsars with ages less than 10^6 which emit high energy γ-rays in Galactic plane with $|b| \leq 5°$. For all these young pulsars, $\sim 22\dot{N}_{100}$ are radio quiet pulsars and $\sim 10\dot{N}_{100}$ are radio pulsars. It is believed that the birth rate of neutron stars in our Galaxy is from 1 to 2 per 100 yr, so the expected young pulsars in $|b| \leq 5°$ are from ~ 32 to ~ 64. Therefore, our model suggests that most unidentified 3EG sources positionally coincident with SNRs or OB star forming regions might be young pulsars. It should be pointed out that the above expectation depends on the detector's sensitivity. For example, if the minimum detectable radio energy flux of pulsar survey is decreased, then more radio pulsars will be detected, and the ratio given above may change. Furthermore, if the minimum detectable γ-ray energy flux decreases, then more young pulsars which emit high energy γ-rays will be detected.

Finally, we consider the dependence of the simulated results on the model parameters. At first, for the initial distributions of the pulsars, the simulated results are not sensitive to the initial period in the range from 10 ms to 30 ms. The variation of the mean magnetic field strength in a reasonable range has little effect on the simulated results. It should be noticed that the initial distributions of the pulsars used here are obtained from the radio pulsar statistical study and we have used them in our γ-ray statistical analysis (Cheng & Zhang 1998), so we believe that they are reliable.



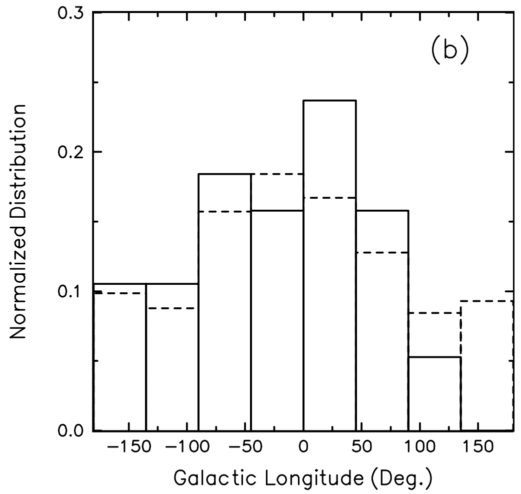


Fig. 6a and b. The normalized distributions of the simulated young pulsars in Galactic latitude and longitude. The distributions of the unidentified EGRET sources whose counterparts are OB associations and SNRs are represented by the solid histograms and those of the simulated young pulsars are represented by dashed histograms. **a** The normalized distribution of Galactic latitude and **b** The normalized distribution of Galactic longitude.

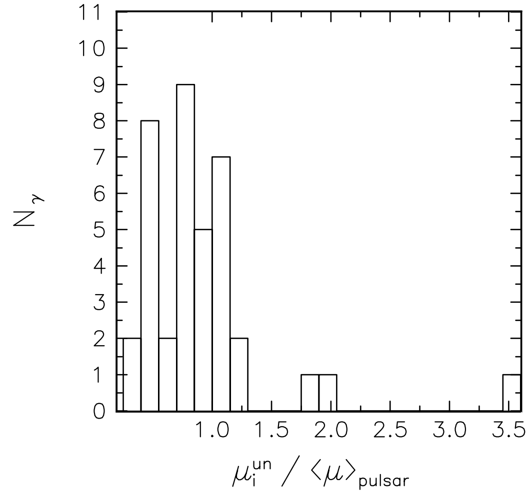


Fig. 7. The distribution of the 38 unidentified EGRET sources with the parameter $I_i = \mu_i^{\rm un}/ < \mu >_{\rm pulsar}$. μ means the fluctuation index which is defined in text.

5. Discussion and conclusions

Based on the study of Romero et al. (1999) on the associations of unidentified EGRET sources with Galactic objects such as SNRs, OB associations as well as WR and Of stars and the γ-ray pulsar model (Zhang & Cheng 1997), we have studied statistical properties of these unidentified EGRET sources using the Monte Carlo method. In our simulations, we have used the initial distributions of the period, position, velocity, magnetic field of the young pulsars obtained from the statistical analysis of radio pulsars. Furthermore, we have generated the total young γ-ray pulsar population which consists of young radio pulsars (population I) and radio-quiet pulsars (population II). The comparison of population I with known γ-ray pulsars shows that our model can explain the statistical properties of γ-ray pulsars. Furthermore, two observed samples (26 OB associations plus 12 SNRs, and 22 SNRs plus 16 OB associations) have been considered. These simulated samples are compared with the observed samples using the KS test. These tests indicate that the unidentified EGRET sources whose counterparts are OB associations and SNRs may have the same parent population as the young pulsars (see Figs. 4 and 5).

We have compared the simulated distance and γ-ray energy flux with the observed data when we tested whether the observed and the simulated have the same parent population. The main reason is that they are independent quantities. In fact, the distances of the counterparts of the unidentified EGRET sources have large uncertainties. For example, for the OB associations the distances are accurate to only $\sim 20\%$. For the SNRs, the distances are even more uncertain. In order to avoid the large uncertainties, we use the distance and γ-ray energy flux as two independent variables instead of the γ-ray luminosity used by Yadigaroglu & Romani (1997).

As mentioned in Sect. 2, there is a possibility that some young SNRs host neutron stars which are still undetected. We have compared the simulated results with the observed sample which consists only of 22 SNRs. These SNRs are coincident spatially with some unidentified EGRET sources (see Table 1). We also list the estimated ages of these SNRs (which are found in the literature) in Table 1. The maximum deviations for the distance and the γ-ray energy flux are 0.392 and 0.207 for the total young γ-ray pulsar population and 0.339 and 0.219 for population II. Furthermore, we have compared the simulated age distribution with the possible age distribution of these SNRs, and we find out that there is a big difference between these two distributions. For example, the maximum deviation from the estimated age in population II is 0.707. Therefore, we may conclude that it is impossible for all unidentified EGRET sources to be young SNRs. We have also made the comparison of the simulated pulsars with the unidentified EGRET sources whose counterparts are OB associations. Although the γ-ray energy flux distributions of the simulated pulsars is consistent with the observed data (the maximum deviations for the total young γ-ray pulsar

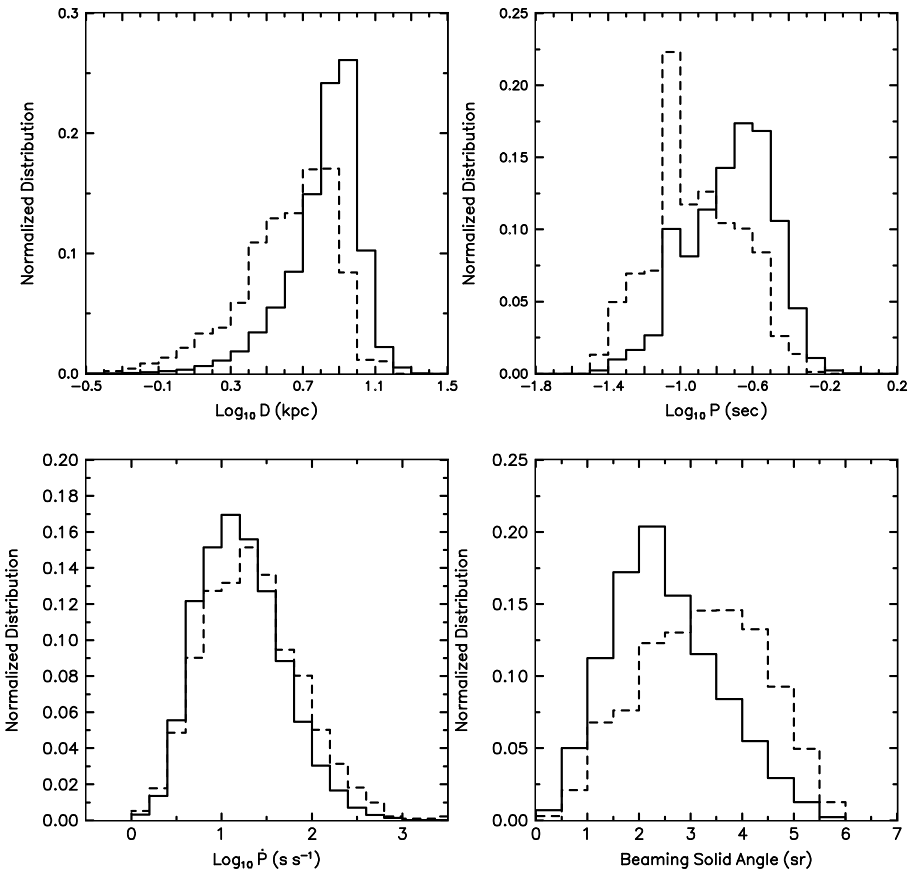


Fig. 8. The normalized distributions of distance, period, period derivative and beaming solid angle for the simulated young pulsars with their ages less than 10^6 yrs. Solid histograms show the distributions of the pulsars in which γ-ray selection effects are taken into account. Dashed histograms show the distributions of the pulsars which are detectable in both radio and γ-ray energy ranges.

population and population II are 0.144 and 0.153 respectively), the distance distributions are not consistent with the observed one (corresponding maximum deviations are 0.284 and 0.330, respectively). So we also have the same conclusion as that for the unidentified EGRET sources whose counterparts are SNRs.

Now we study the variability of 38 unidentified γ-ray sources listed in Table 1. We use the weigthed fluctuation index μ used by Romero et al. (1994) for blazar variability, i.e. $\mu = 100\sigma_S / < S >$, where $< S > = [\Sigma_{i=1}^{n} \sigma_i^{-2} S_i][\Sigma_{i=1}^{n} \sigma_i^{-2}]^{-1}$ is the weighted mean flux density of a source and σ_S is the standard deviation of the set of n measurements. In 3EG catalog, there are many observations at different viewing periods for one source. When the source has just an upper flux limit in 3EG catalog, we assume that the flux is $F_\gamma = (F_\gamma^{\rm upper} - F_\gamma^{\rm lim})/2$ with errors of the same magnitude, where $F_\gamma^{\rm lim} \approx 6.2 \times 10^{-8}$ cm^{-2} s^{-1}. First, we estimate the index for the 6 known γ-ray pulsars. In the 3EG catalog, the fluxes observed at different viewing periods for five known γ-ray pulsars (Crab, Geminga, Vela, PSR B1055-52 and PSR B1706-44) are given. For PSR B1951+32, we use the observed fluxes given by Fierro (1995) (also see Mamanamurthy et al. 1995). Averaging the μ values of these pulsars, we have $< \mu >_{\rm pulsar} = 77.0 \pm 50.0$. Further we estimate the index $\mu_i^{\rm un}$ of the 38 unidentified γ-ray sources. Then we define a parameter $I_i = \mu_i^{\rm un} / < \mu >_{\rm pulsar}$. A source can be considered as variable when its parameter I is greater than $1 + 1\sigma$, otherwise the source classifies as non-variable. We list the values of this parameter for 38 unidentified sources in Table 1. In Fig. 7, we present the distribution of these unidentified sources with this parameter. From Table 1 and Fig. 7, 26 of 38 unidentified sources have values of I_i which are less than 1 and $I_i \le 1 + 1\sigma$ for 35 sources. There are 3 sources that are clearly differentiated from the rest. The most variable of these sources has a spectral index of 2.71, clearly incompatible with a pulsar interpretation. All variable sources are also positionally consistent with SNRs. These facts suggest an interpretation based on isolated black holes for such sources. More research should be done on them in the future. Therefore it seems that most of the 38 unidentified sources are non-variable. However it should be noted that the standard error of mean fluctuation index of known γ-ray pulsars is large, so we cannot confirm the above conclusion using current observed data.

It is interesting to give some expectations using our model for GLAST threshold. For the point sources, the GLAST sensitivity for the γ-rays with energy greater than 100 MeV is $\sim 4 \times 10^{-9}$ cm^{-2} s^{-1} (Kamae et al. 1999), which means that the ratio of GLAST threshold to EGRET threshold is $\sim 4 \times 10^{-2}$. Assuming that the minimum detectable energy flux of the GLAST is 4.8×10^{-12} erg cm^{-2} s^{-1}, we have produced two samples of γ-ray pulsar populations with the pulsar ages less than 10^6 yr. One consists of the γ-ray pulsars in which only γ-ray selection effects are taken into account, the other consists of the young pulsars which are detectable in both radio and γ-ray energy ranges. The normalized distributions of the distance, period, period derivative and beaming solid angle are shown in Fig. 8. Our results indicate that (i) the GLAST may detect $\sim 80\dot{N}_{100}$ radio pulsars and (ii) if most unidentified γ-ray point sources in $|b| \leq 5°$ are young pulsars, then the GLAST may detect $\sim 1100\dot{N}_{100}$ Galactic γ-ray point sources.

The observations of γ-ray pulsars indicate that the pulsar spectrum is not too steep; the maximum value of the spectral indices for the known γ-ray pulsars is about 2.19 (the Crab pulsar). From Table 1, however, 33 out of the unidentified 3EG sources which are coincident with OB associations and SNRs have spectral indices of less than 2.5, so it is difficult to say whether the unidentified γ-ray sources in the Galactic plane can be explained in form of the young pulsar origin only by spectral analysis.

Finally, we would like to emphasize that there may be other origins for the unidentified EGRET sources in the Galactic plane although our results favor a young pulsar origin. Sturner & Dermer (1995) pointed out that some of the unidentified EGRET sources are coincident with SNRs and have SNR origin. However, the γ-rays from SNRs come from the interaction between high energy particles accelerated at the supernova shock front and swept-up material. The γ-ray flux from a SNR is expected to be rather low (Drury et al. 1994) unless there is a cloud near the particle acceleration site (Aharonian et al. 1994; Combi et al. 1998).

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