Contribution to diffuse gamma-rays in the Galactic center region from unresolved millisecond pulsars

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ABSTRACT

The diffuse gamma-rays in the Galactic center region have been studied. We propose that there exists a population of millisecond pulsars (MSPs) in the Galactic Center, which will emit GeV gamma-rays through the synchrotron-curvature radiation as predicted by outer gap models. These GeV gamma-rays from unresolved millisecond pulsars probably contribute to the diffuse gamma-ray spectrum detected by EGRET which displays a break at a few GeV. We have used the Monte Carlo method to obtain the simulated samples of millisecond pulsars in the Galactic center region covered by EGRET (≈ 1.5°) according to the different period and magnetic field distributions from the observed millisecond pulsars in the Galactic field and globular clusters, and superposed their synchrotron-curvature spectra to derive the total GeV flux. Our simulated results suggest that there probably exist about 6000 unresolved millisecond pulsars in the region of the angular resolution for EGRET, whose emissions could contribute significantly to the observed diffuse gamma-rays in the Galactic center.

Key words: Galaxy: center – gamma-rays: theory – pulsar: general – radiation mechanisms: nonthermal

1 INTRODUCTION

Gamma-ray emissions have been detected from the Galactic center (GC) region (Churazov et al. 1994). EGRET on board the Compton GRO has identified a central (< 1°) ~ 30 MeV – 10 GeV continuum source (2EG J1746-2852) with a luminosity of ~ 10^{37} erg s^{-1} (Mattox et al. 1996). Further analysis of the EGRET data obtained the diffuse gamma ray spectrum in the Galactic center. Allowing for a total source-excess extent up to 1.5 degree in radius, the luminosity (> 100 MeV) attributed to the source excess at GC is about 2 × 10^{37} erg s^{-1} (Mayer-Hasselwander et al. 1998). The photon spectrum can be well represented by a broken power law with a break energy at ~ 2 GeV. Below this energy the differential photon spectrum is \( F(E) = 2.2 \times 10^{-10} (E/1900\text{MeV})^{-1.3} \), above the break energy the spectrum is \( F(E) = 2.2 \times 10^{-10} (E/1900\text{MeV})^{-3.1} \). A re-analysis of EGRET data by Hooper and Dingus (2002) has shown that the EGRET GeV source is displaced from the GC. Recently, Tsukuba et al. (2004) have detected sub-TeV gamma-ray emission from the direction of the Galactic Center using the CANGAROO-II Imaging Atmospheric Cherenkov Telescope. Their data suggest that the GeV source 3EG J1746-2851 may be coincident with this TeV source. Recent observations of the GC with the air Cerenkov telescope HESS (Aharonian et al. 2004) have shown a significant source centered on Sgr A* above energies of 165 GeV with a spectral index \( \Gamma = 2.21 \pm 0.09 \).

Some researchers have studied the possible origin of the gamma-rays from GC. Mastichiadis & Ozeino (1994) provided that the gamma-rays originate close to the massive black hole (\( M_{BH} \sim 10^6 M_{\odot} \)), possibly from relativistic particles accelerated by a shock in the accreting plasma. In the same time, the gamma-rays could come from some extended features like radio arcs, where relativistic particles are present (Pohl 1997). Markoff et al. (1997) discussed in detail the gamma-ray spectrum of GC produced by synchrotron, inverse Compton scattering, and mesonic decay resulting from the interaction of relativistic protons with hydrogen accreting onto a point-like sources (e.g. the massive black hole).

However, the above models cannot produce the hard gamma-ray spectrum with a sharp turnover at a few GeV, which is observed for the GC source. On the other hand, the spectrum is similar with the gamma-ray spectrum emitted by middle-aged pulsars and millisecond pulsars (Zhang & Cheng 2003; Cheng et al. 2004). Because of the high gamma-ray luminosity observed in GC, we may require a pulsar population in the inner region. In the following, we will first argue that canonical pulsars (including young and mature pulsars) may not be a major contributor to the pulsar population in GC.

Young pulsars are not likely to be a major contribu-
tor since few supernova remnants are presently observed in the Galactic center field targeted in the deep X-ray surveys (Wang et al. 2002a; Muno et al. 2003). This viewpoint is also supported by pulsar birth rate estimates. Specifically, the birth rate of young pulsars in the Milky Way is about 1/150 yr (Arzoumanian, Chernoff, & Cordes 2002). As the mass in the inner 20 pc of the Galactic center is \( \sim 10^6 M_\odot \) (Launhardt, Zylka, & Mezger 2002), the birth rate of young pulsars in this region is only \( 10^{-3} \) of that in the entire Milky Way, or \( \sim 1/150 \) 000 yr. We note that the rate may be increased to as high as \( 1/15000 \) yr in this region if the star formation rate in the nuclear bulge was higher than in the Galactic field over last \( 10^7 - 10^8 \) yr (see Pfahl et al. 2002).

Few young pulsars are likely to remain in the Galactic center region since only a fraction (\( \sim 40\% \)) of young pulsars in the low velocity component of the pulsar birth velocity distribution (Arzoumanian, Chernoff, & Cordes 2002) would remain within the 20 pc region of the Galactic center studied by Muno et al. (2003) on timescales of \( \sim 10^7 \) yrs. Mature pulsars can remain active as gamma-ray pulsars up to \( 10^8 \) yr, and have the same gamma-ray power with millisecond pulsars (Zhang et al. 2004; Cheng et al. 2004a), but according to the birth rate of pulsars in GC, the number of gamma-ray mature pulsars is not higher than 10.

On the other hand, there may exist a population of old neutron stars with low space velocities which have not escaped the Galactic center (see Belczynski & Taam 2004). Such neutron stars could have been members of binary systems and been recycled to millisecond periods, having formed from low mass X-ray binaries in which the neutron stars accreted sufficient matter from either white dwarf, evolved main sequence star or giant donor companions (Belczynski & Taam 2004, in preparation). The current population of these millisecond pulsars may either be single (having evaporated its companion) or have remained in a binary system. Cheng et al. (2004b) provide that wind nebulae of the millisecond pulsar population in the Galactic center region can contribute to the unidentified X-ray sources in GC by the Chandra survey (Wang et al. 2002a; Muno et al. 2003).

Because millisecond pulsars also remain active as gamma-ray pulsars, radiating gamma-rays through the synchrotron-curvature process (Cheng & Zhang; 1996; Zhang & Cheng 2003), it is possible that the observed gamma-ray luminosity in GC may be produced through an accumulation of these millisecond pulsars which would provide the observed gamma-ray spectrum.

In this paper, we will examine in detail if the millisecond pulsar population could contribute to the diffuse gamma-ray spectrum in the Galactic center region. In §2, we will present our motivation to consider the contribution of millisecond pulsars to diffuse gamma-ray in GC based on the outer gap model. To find the gamma-ray spectrum of these millisecond pulsars, we assume their globular parameters like the period, magnetic field are similar to those of the observed millisecond pulsars. In §3, we derive the period, magnetic field distributions of total MSPs, MSPs in the Galactic field and in globular clusters from the present pulsar survey database. In §4, we sample millisecond pulsars by the Monte Carlo method according to the different distributions, superpose their spectral profiles to fit the observed diffuse gamma-ray spectrum in GC and obtain the number of MSPs which are needed in the Galactic center region covered by EGRET.

Our results are summarized and discussions are also presented in §5.

### 2 Motivations

Since the mass within the region with the radius \( \sim 20 \) pc (\( 17' \times 17' \)) of the Galactic center is \( \sim 10^6 M_\odot \) (Launhardt, Zylka & Mezger 2002), an estimate for the fraction of millisecond pulsars in this region is \( \sim 10^{-3} \) of the entire Galaxy. Based on the population analysis of Lyne et al. (1998), the number of millisecond pulsars in the entire Galaxy may exceed \( 2 \times 10^7 \), suggesting that more than 200 millisecond pulsars exist in the Galactic center region if their evolutionary formation channels are similar to the rest of the Galaxy. Coupled with the fact that the escape velocity from the Galactic center is about 200 km s\(^{-1}\) and the average birth velocities of observed millisecond pulsars are \( \sim 130 \) km s\(^{-1}\) (Lyne et al. 1998), these pulsars are likely to remain in the Galactic center through their entire lifetime. Belczynski \\& Taam (2004) have considered the binary population synthesis in the Galactic center region, and their results show that there exist about 300 low-mass binary systems in the Galactic center. Furthermore, about 100 - 200 millisecond pulsars could be produced through the recycle scenario and lie in the Galactic center region (\( 17' \times 17' \), Taam 2004, private communication). Recently, Pfahl \\& Loeb (2004) propose that \( \sim 1000 \) radio pulsars may presently orbit Sgr A* with periods of \( \leq 100 \) years, in which 1-10 may be detected by current radio telescopes. Therefore, we believe that there should exist a millisecond pulsar population in the Galactic center, which can contribute to the high energy emissions, e.g. X-rays, gamma-rays which are detectable.

Millisecond pulsars can remain active as gamma-ray pulsars through their lifetime according to outer gap models which are originally proposed by Cheng, Ho \\& Ruderman (1986). Based on the model, Zhang \\& Cheng (1997) have developed a self-consistent mechanism to describe the high energy radiation from spin-powered pulsars. In the model, relativistic charged particles from a thick outer magnetospheric accelerator (outer gap) radiate through the synchrotron-curvature radiation mechanism (Cheng \\& Zhang 1996) rather than the synchrotron and curvature mechanisms in general, producing non-thermal photons from the primary \( e^\pm \) pairs along the curved magnetic field lines in the outer gap. The characteristic energy of high energy photons emitted from the outer gap is determined by the global pulsar parameters, including the spin period \( P \), the dipolar magnetic field \( B \), and the fractional size of the outer gap \( f = 5.5 P^{26/21} B_{12}^{−4/7} \) (Zhang \\& Cheng 1997), which is the ratio between the mean vertical separation of the outer gap boundaries in the plane of the rotation axis and the magnetic axis to the light cylinder radius. Then the characteristic synchrotron-curvature emission energy is given by (Zhang \\& Cheng 1997)

\[
E_γ \simeq 5 \times 10^7 P^{1/2} B_{12}^{3/4} f^{-7/4} \frac{r}{R_L}^{-11/8} \text{eV},
\]

where \( B_{12} \) is the dipolar magnetic field in units of \( 10^{12} \) G, \( R_L = cP/2\pi \) is the light cylinder radius, and \( r \) is the distance to the neutron star. The gamma-ray spectrum drops exponentially beyond the energy \( E_γ \). This self-consistent model
has also been developed to describe gamma-ray emission from millisecond pulsars (Zhang & Cheng 2003).

Zhang & Cheng (1998) have studied the contribution to the Galactic diffuse gamma-rays from the unresolved spin-powered pulsars using the outer gap model. Their results show that the gamma-ray emission from these pulsars could contribute significantly to the observed Galactic diffuse gamma-ray spectrum above 1 GeV. Therefore, we believe that a large number of millisecond pulsars which lie in the Galactic center and for surface magnetic field distribution are $B_{\text{surf}} < 10^{7}$ G. On the other hand, the measurement of millisecond pulsars in the Galactic field and globular clusters separately. We should notice that a large number of millisecond pulsars which lie in the Galactic center region could also contribute significantly to the diffuse gamma-ray spectrum from the Galactic center. Furthermore, according to the results of Zhang & Cheng (2003), the gamma-ray spectral cut-off at $\sim$ a few GeV is consistent with the observed spectral properties of diffuse gamma-rays in the Galactic center.

To study the contribution of millisecond pulsars to the diffuse gamma-ray radiation from the Galactic center in detail, e.g. fitting the spectral properties and total luminosity, we firstly need to derive the period and surface magnetic field distribution functions of the millisecond pulsars respectively. And then we integrate contributions from all the millisecond pulsars with different periods and surface magnetic fields to derive the predicted diffuse gamma-ray spectrum, which can be compared with the observed spectrum in the Galactic center region to calculate how many MSPs are needed. This is the aim of the present paper.

3 DISTRIBUTION FUNCTIONS OF MILLISECOND PULSARS

We obtain the period and surface magnetic field distribution functions of millisecond pulsars from the observed pulsar data. Here, millisecond pulsars are defined as the pulsar with $P < 10$ ms, and $B_{\text{surf}} < 10^{10}$ G. So we find 86 detected millisecond pulsars from the latest ATNF Pulsar Catalog 1, in which 41 millisecond pulsars are in the Galactic field, and 45 pulsars in globular clusters. Since the millisecond pulsars in the Galactic field and globular clusters may have different properties, we derive the distribution functions of total millisecond pulsars at first, and then the distribution functions of the millisecond pulsars in the Galactic field and globular clusters separately. We should notice that the period derivative measurement of millisecond pulsars in globular clusters is quite difficult and uncertain, so many of them have not been given the surface magnetic field, and the magnetic field varies from $10^8$ G to $10^{10}$ G. On the other hand, the measurement of the millisecond pulsars in the Galactic field is relatively accurate and reliable, the derived surface magnetic field is lower than $10^9$ G.

When fitting the normalized distribution profile, we take the Gaussian function as the following form

$$f(x) = f_0 + \frac{A}{W \sqrt{\pi/2}} \exp[-2(x-x_c)^2/W].$$

(2)

To derive the period distribution function, we define $x = P$ and $1 ms < P < 10$ ms, and for surface magnetic field distribution function, $x = \log B_{\text{surf}}$. If including the total millisecond pulsars, the fitting parameters for the period distribution are $f_0 = 0.045, A = 0.60, W = 1.95, x_c = 3.91$; for magnetic field distribution, the parameters are $f_0 = 0.015, A = 0.17, W = 0.57, x_c = 8.49$ ($7.8 < \log B < 10$).

The fitting profiles of the pulsar data have been shown in Figure 1. Just including the millisecond pulsars in the Galactic field, the parameters for the period distribution are $f_0 = 0.050, A = 0.48, W = 2.34, x_c = 4.28$; the parameters for magnetic field distribution are $f_0 = -0.06, A = 0.24, W = 0.65, x_c = 8.40$ ($7.8 < \log B < 9$) (Figure 2). Only including the millisecond pulsars in globular clusters, the parameters for the period distribution are $f_0 = 0.042, A = 0.67, W = 1.62, x_c = 3.71$; the parameters for magnetic field distribution are $f_0 = 0.04, A = 0.10, W = 0.37, x_c = 8.71$ ($7.8 < \log B < 10$) (Figure 3).

4 SPECTRAL MODELLING OF DIFFUSE GAMMA-RAYS OF THE GALACTIC CENTER

As discussed in Section 2, there exists the population of millisecond pulsars in the Galactic center region. Firstly, we assume the number of MSPs, $N_{\text{MSP}}$, in GC within the angular resolution size of EGRET $\sim 1.5^\circ$, each of them with an emission solid angle $\Delta \Omega \sim 1$ sr and the $\gamma$-ray beam pointing in the direction of the Earth. We performed calculations to sample the parameters (period and magnetic field) of these MSPs by the Monte Carlo method using the above three distributions of the observed MSPs derived in Section 3. Here, we have assumed no evolution for these millisecond pulsars, and they will remain to lie in the Galactic center because of their low average proper motion velocity (see Lyne et al. 1998; Arzoumanian, Chernoff, & Cordes 2002).

Zhang & Cheng (2003) have proposed a model to describe the X-ray and $\gamma$-ray emission from MSPs with outer gaps. We first calculate the fractional size $f_m$ of the outer gap in our simulated MSPs, if $f_m < 1$, the outer gap can exist and then the MSP can emit high energy $\gamma$-rays, $f_m$ can be estimated by (Zhang & Cheng 2003)

$$f_m \approx 7.0 \times 10^{-2} \delta r_3^{17/2} \frac{B}{10^8 \text{G}}^{3/7} \delta r_5^{2/7}$$

(3)

where $\delta r$ is the distance where the local magnetic field equal to the dipole field, in the following calculations, we assume $\delta r_5 = \delta r/10^5 \sim 1$. The $\gamma$-rays are produced in the outer gap by synchrotron-curvature radiation, the $\gamma$-ray differential flux observed on the Earth of the $i$th MSP can be calculated by

$$F_i(E_{\gamma}) = \frac{1}{\Delta\Omega d^2} \frac{d^2N_i}{dE_{\gamma} dt}$$

(4)

where $d$ is the distance of the Galactic center to us, taken as 8.0 kpc, the solid angle of $\gamma$-ray beam $\Delta \Omega \sim 1$ sr, the spectrum $d^2N/dE_{\gamma} dt$ can be calculated according to the equation (57) of Zhang & Cheng (1997). The total flux which contributes to the $\gamma$-ray emission from the GC region can be obtained by superposing all MSPs with outer gaps

$$F(E_{\gamma}) = \sum_{i=1}^{n} F_i(E_{\gamma})$$

(5)

where $n$ is the number of simulated MSPs with outer gaps.
During our calculations, we let the number of millisecond pulsars $N_{\text{MSP}}$ as a free parameter to fit the observed data points using three different distributions of the period and magnetic field separately. We find that about 6000 MSPs could significantly contribute to the observed GeV flux in the Galactic center region. The calculated profiles of superposed spectra of the all millisecond pulsars with outer gaps in the Galactic center region according to three different distributions of the period and magnetic field are shown in Figure 4. The solid line corresponds to the distributions derived from the total detected millisecond pulsars; the dashed line just includes the millisecond pulsars in the Galactic field; and the dotted line just includes the millisecond pulsars in globular clusters. Our predicted spectra are consistent with the observed results which have been analyzed by Mayer-Hasselwander et al. (1998) and Hartman et al. (1999).

In Figure 4, one can find that the predicted spectra calculated due to the distributions derived from the total observed millisecond pulsars and those just in globular clusters fit the observed data better. The reduced $\chi^2$ values of three curves fitting to the eight data points are 1.51 (solid line), 3.95 (dashed) and 1.62 (dotted) respectively. Our results probably imply that the unresolved millisecond pulsars in GC will follow the period and magnetic field distributions similar to the forms observed in globular clusters. However, the number of discovered millisecond pulsars is very limited at present, so the statistics may be quite uncertain. In addition, the predicted flux is dependent on some pulsar global parameters, so it is too early to make the conclusion. Meanwhile, it should be pointed that the different profiles of predicted spectra could also be induced by the different number of simulated millisecond pulsars with outer gaps (satisfying the criterion $f_m < 1$): about 4000 simulated MSPs have outer gaps according to the distributions just including the MSPs in the Galactic field; while, about 5000 MSPs can have outer gaps for the derived distributions of total observed MSPs and those in globular clusters. For the distributions of MSPs in the field, even if we increase the number to $N_{\text{MSP}} \sim 10000$, the predicted spectrum fits the data not better than the solid and dotted lines in Figure 4. After checking the simulated data, we find that according to the distributions in the field, the number fraction of simulated MSPs which satisfies the criterion $f_m < 1$ is small, and the average $\gamma$-ray luminosity of MSPs is relatively low.

Furthermore, the fraction size of the outer gap $f_m$ will determine the total flux of millisecond pulsars, i.e. $F_\gamma \propto f_m^4$. Zhang et al. (2004) considered the effect of the magnetic inclination angle in the calculation of $f_m$, and found that $f_m$ for the large magnetic inclination angle can increase to 2-3 times of the original value. Millisecond pulsars generally have a large magnetic inclination angle (Ruderman 1991), then they can emit the higher gamma-ray flux, so the required number of millisecond pulsars in the region with the radius of $\sim 1.5^{\circ}$ to produce the diffuse gamma-rays in GC can decrease significantly. Even considering part of millisecond pulsars have no outer gaps when $f_m$ is larger, the simulated number of millisecond pulsars which can fit the spectra best is $N_{\text{MSP}} \sim 1000$ for the distributions of MSPs in globular clusters and total observed MSPs, $N_{\text{MSP}} \sim 2000$ for the distributions of MSPs in the field. Probably, these decreasing numbers of MSPs in GC are more reasonable both for the theoretical prediction and observations.

5 DISCUSSIONS AND CONCLUSION

In the present paper, we have studied the diffuse gamma-rays in the Galactic center region detected by EGRET. We propose that there exists the population of millisecond pulsars in the Galactic center, which will emit gamma-rays through synchrotron-curvature radiation predicted in the outer gap models. The gamma-ray spectrum of millisecond pulsars shows a break at a few GeV, which is similar to the spectrum of diffuse gamma-rays in GC. Therefore, these unresolved millisecond pulsars could contribute to a significant fraction of diffuse gamma-rays in GC.

According to the period and magnetic field distributions of the observed millisecond pulsars, we sampled the global parameters (period and magnetic field) of the millisecond pulsar population in the Galactic center region by the Monte Carlo method. Since the millisecond pulsars in the Galactic field and globular clusters may have different properties, we find three classes of distributions which include total observed MSPs, just include the MSPs in the field and those in globular clusters, respectively. Then we used three possible MSP samples to calculate their gamma-ray differential spectra, and superpose the profiles to fit the observed data. The modelled results suggest about 6000 MSPs are needed to match the observed gamma-ray spectrum. We also find the superposed spectra of MSPs could fit the observed spectrum well except for the sample derived from the distributions of the MSPs in the field (see Figure 4), which probably suggests the unresolved millisecond pulsars in the Galactic center follow the distributions of the period and magnetic field similar to the forms in globular clusters. However, because the number of millisecond pulsars in globular clusters with the period and period derivative measurements is limited, and the number of millisecond pulsars in GC is also unknown, we cannot conclude that the hypothetical millisecond population in GC could resemble millisecond pulsars in globular clusters at present. Furthermore, if the effect of the magnetic inclination angle is considered in the calculation of the fraction size of the outer gap $f_m$, at least about 1000 millisecond pulsars for the different distribution are still required in the region of the radius $\sim 1.5^{\circ}$ to fit the diffuse gamma-ray spectrum in the Galactic center.

The multiwavelength observations have shown the complex structure in the GC region (e.g. Purcell et al. 1997; Mayer-Hasselwander et al. 1998; Wang et al. 2002a; Maeda et al. 2003), so different scenarios for the origin of the diffuse gamma-rays have been considered as mentioned in §1 (also see Mayer-Hasselwander et al. 1998 and references therein). Recently, Fatuzzo & Melia (2003) have attributed theGeV emission to $\pi^0$ decay resulting from high energy protons interacting with the ambient matter in Sgr A East. As pointed out in Mayer-Hasselwander et al. (1998), those models cannot easily produce the very hard spectrum with a sharp turnover. In this paper, we suggested that the spectrum turnover may be contributed by the millisecond pulsar population in GC through curvature-synchrotron radiation in the magnetosphere. The predicted spectrum of millisecond pulsars show a cutoff above $\sim 3$ GeV (see Figure 4), so
it cannot contribute to the sub-TeV flux recently detected by CANGAROO-II (Tsuchiya et al. 2004) and HESS (Aharonian et al. 2004). $L_{\text{TeV}} \sim 10^{34}\text{erg s}^{-1}$. These TeV photons in GC are possibly induced by pion decay produced through $pp$ interactions (e.g. Tsuchiya et al. 2004 and references therein), and compact wind nebulae of millisecond pulsars through inverse Compton scattering (e.g. Aharonian, Atoyan & Kifune 1997; Wang et al. 2004). According to the estimation of Wang et al. (2004), the TeV luminosity of the MSP wind nebula through inverse Compton scattering is $\sim 10^{31}\text{erg s}^{-1}$, with $L_{\text{TeV}} > 10^{33}\text{erg s}^{-1}$. The average medium density $n \sim 10^7\text{cm}^{-3}$ and magnetic field in the Galactic center region $B \sim 50\mu\text{G}$ (Uchida & Güsten 1995), then the total TeV luminosity contributed by wind nebulae of MSPs is $\sim 6 \times 10^{32}\text{erg s}^{-1}$. Compared with the present observations, we think compact wind nebulae of millisecond pulsars through inverse Compton scattering could contribute to the TeV flux in the Galactic center, and the photon index $\Gamma \sim 2.2$ is also well within the predicted range by wind nebula models $\Gamma \sim 2 - 2.5$ (e.g. Wang et al. 2004). Hence, the origin of high energy gamma-rays (GeV - TeV energy band) is still a mystery, requiring the further observational constraints.

Michelson et al. (1994) have derived an upper limit to $>$ 100 MeV luminosity of the globular cluster 47 Tuc, where over 20 millisecond pulsars have been identified and an estimated total population could be larger than 200 (Camilo et al. 2000). Using the EGRET observed upper limit of 47 Tuc ($\sim 1.2 \times 10^{35}\text{erg s}^{-1}$) with the estimate MSP population, the estimated gamma-ray luminosity for individual MSP is roughly $6 \times 10^{32}\text{erg s}^{-1}$, which is lower than our estimate in this paper. However, Cheng and Taam (2003) have studied the X-ray properties of the MSPs in 47 Tuc, in which the average X-ray luminosity per MSP is about factor 10 lower than those typical MSPs in the field and the spectrum is dominated by thermal spectrum with an unusually high polar cap temperature. They conclude that all these unusual properties can be explained by the fact that strong, small-scale, multipole magnetic fields exist on the surface of MSPs in the 47 Tuc. They suggest that the typical age of MSPs in globular cluster is much older than those in the field, therefore the surface magnetic field buried under the crust during the accretion phase may diffuse back to the surface in billion year time scales. They also suggest that these complicated surface magnetic field structure can quench the outer gap because gamma-rays emitted from the polar gap can become pairs in those magnetic field lines connected with outer gap (Ruderman and Cheng 1988). Therefore they suggest that MSPs in 47 Tuc are weak gamma-ray emitters.

Here, we would like to emphasize two important points again. First, the evolution of magnetic field of millisecond pulsars in 47 Tuc could be very special. In section 5 of Cheng and Taam (2003), who have argued that the density of star in 47 Tuc is so high that there could be more than one exchange collision or tidal capture to form a close interacting binary system in 47 Tuc. Consequently, the spin-up (or spin-down) evolution during accretion (or post accretion) phase of a millisecond pulsar in 47 Tuc can be very much different from the evolution of other millisecond pulsars. They argue that the results in complicated surface magnetic field structure quench the outer magnetospheric gaps as suggested by Ruderman and Cheng (1988). Therefore, the low gamma-ray flux from 47 Tuc may not imply all millisecond pulsars in globular cluster emitting weak gamma-ray flux. Secondly, if we allow number of millisecond pulsars in the field increase by a factor of 50%, then the population of millisecond pulsars in the field can give an equally good fit as those two previous cases. Therefore we cannot conclude that the hypothetical millisecond population in GC should resemble either millisecond pulsars in the field or millisecond pulsars in globular cluster from the current data.

We would like to remark that the spectral break of the gamma-ray spectrum depends on three pulsar parameters, i.e. period, magnetic field and the inclination angle ($\alpha$) of pulsars. The first two parameters can be determined in very good accuracy, however, the last parameter is difficult to be determined accurately. Zhang and Cheng (2003) have calculated some model dependent gamma-ray spectra for MSPs. They have chosen various inclination angles for different MSPs. For PSR J0437-4715 and PSR J2124-3358, they choose larger inclination angle ($\alpha \sim 40^\circ$), the model spectral breaks occur at about 3 GeV (cf. Fig. 1 of Zhang & Cheng 2003). On the other hand, for PSR J0218+4232 and PSR B1821-24 they choose ($\alpha \sim 55^\circ$), the spectral breaks occur at about 10 GeV (cf. Fig. 2 of Zhang & Cheng 2003). Cheng et al. (2004a) have also studied that effect of inclination angle on the gamma-ray spectrum, indeed, the spectrum is quite sensitive to this parameter (cf. Fig. 1 of Cheng et al. 2004a). In their study they find that pulsars in the galactic plane are younger and have larger inclination angle whereas pulsars in medium and high galactic latitude are older and have smaller inclination angles. They have used a Monte Carlo simulation method to show that if the distribution of pulsar inclination angle satisfies a random distribution (Biggs 1990), then they find that the gamma-ray spectral break of galactic pulsars are higher than those in high latitude by a factor of 3. Although there are very few confirmed gamma-ray millisecond pulsars, i.e. only three possible candidates in EGRET catalog with 3 $\sigma$ level (Fierro 1995) and one good candidate PSR J0218+4232 (Kuiper et al. 2000), we believe that high energy satellites, like Integral, GLAST, can very soon provide more information for us about the spectral behavior of MSPs.

Finally, we are aware that the millisecond pulsar population in the Galactic center region is still an assumption at present because there are no MSPs discovered in the inner region. We think the assumption would be reasonable if compared with the observed MSPs in the Galaxy, specially many MSPs discovered in the systems of globular clusters, e.g. 47 Tuc (Grindlay et al. 2002), and an estimated total number over 200 MSPs (Camilo et al. 2000). In theory, the binary population synthesis in the Galactic center region also suggested that there are hundreds of MSPs in GC (Belczynski & Taam 2004; Taam 2004, private communication). However, because the electron density in the direction of GC is very high (Cordes & Lazio 2002), it is difficult to detect millisecond pulsars by the present radio telescopes.² X-ray studies

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² The Parkes telescope has performed a short-time survey covering the region of GC, no pulsars have been reported in the initial results (Wang, N. & Manchester, D. 2004, private communication).
of the sources in GC would probably be a feasible method to find millisecond pulsars by Chandra and XMM-Newton. Recent deep X-ray surveys of the Galactic center have found a large number of unidentified faint X-ray sources (Wang et al. 2002a; Muno et al 2003). Cheng et al. (2004b) have suggested that synchrotron X-ray nebulae around millisecond pulsars could contribute to a fraction of these sources, and the sources with tailed features would be the good candidates. Some bright X-ray tails probably coincident with radio filaments have been suggested to be the pulsar wind nebulae after the image and spectral analyses (Wang, Lu & Lang 2002b; Lu, Wang & Lang 2003; Sakano et al. 2003). In a word, though still in dispute, the millisecond population in GC is suggestive, which could contribute to faint X-ray sources and diffuse gamma-rays in GC as studied in this paper.

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Figure 1. The distributions of the period (up) and surface magnetic field (bottom) of total detected millisecond pulsars. The dashes lines are the fitting curves using the Gaussian function.

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Contribution to diffuse gamma-rays in the Galactic center region from unresolved millisecond pulsars

Figure 2. The distributions of the period (up) and surface magnetic field (bottom) of the detected millisecond pulsars in the Galactic field. The dashes lines are the fitting curves using the Gaussian function.

Figure 3. The distributions of the period (up) and surface magnetic field (bottom) of the detected millisecond pulsars in globular clusters. The dashes lines are the fitting curves using the Gaussian function.
Figure 4. Simulated spectra of millisecond pulsars (assumed \( N_{\text{MSP}} = 6000 \)) in our model compared with observed gamma-ray energy distribution of the Galactic center region by EGRET. The data points are taken from the analyses of Hartman et al. (1999) and Mayer-Hasselwander et al. (1998). The lines represent the integrated fluxes from millisecond pulsars according to three different distributions (period and magnetic field) of millisecond pulsars assumed in the Galactic center, respectively. The solid line corresponds to the distributions derived from the total detected millisecond pulsars; the dashed line just includes the millisecond pulsars in the Galactic field; and the dotted line just includes the millisecond pulsars in globular clusters.