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

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ABSTRACT
Diffuse gamma-rays in the Galactic Centre region have been studied. We propose that there exists a population of millisecond pulsars in the Galactic Centre, which emit GeV gamma-rays through 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 a Monte Carlo method to obtain simulated samples of millisecond pulsars in the Galactic Centre region covered by EGRET (~1:5) according to the different period and magnetic field distributions from 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 angular resolution of EGRET, the emissions of which could contribute significantly to the observed diffuse gamma-rays in the Galactic Centre.

Key words: radiation mechanisms: non-thermal – pulsars: general – Galaxy: centre – gamma-rays: theory.

1 INTRODUCTION
Gamma-ray emissions have been detected from the Galactic Centre (GC) region (Churazov et al. 1994). EGRET on board the Compton Gamma-Ray Observatory 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 GC. Allowing for a total source excess extent up to 1:5 in radius, the luminosity (>100 MeV) attributed to the source excess at the GC is about 2 x 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 x 10^{-10}(E/1900 MeV)^{-1.3}; above the break energy the spectrum is F(E) = 2.2 x 10^{-10}(E/1900 MeV)^{-3.1}. A re-analysis of EGRET data by Hooper & Dingus (2004) has shown that the EGRET GeV source is displaced from the GC. Recently, Tsuchiya et al. (2004) have detected sub-TeV gamma-ray emission from the direction of the GC using the CANGAROO-II Imaging Atmospheric Cherenkov Telescope. Their data suggest that the GeV source 3EG 1746 – 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 centred on Sgr A* above energies of 165 GeV with a spectral index Γ = 2.21 ± 0.09.

Some researchers have studied the possible origin of the gamma-rays from the GC. Mastichiadis & Ozernoy (1994) showed that the gamma-rays originate close to the massive black hole (M_{BH} ~ 10^6 M_{⊙}), possibly from relativistic particles accelerated by a shock in the accreting plasma. At the same time, the gamma-rays could come from some extended features like radio arcs, where relativistic particles are present (Pohl 1997). Markoff, Mella & Sarcevic (1997) discussed in detail the gamma-ray spectrum of the GC produced by synchrotron radiation, inverse Compton scattering, and mesonic decay resulting from the interaction of relativistic protons with hydrogen accreting on to a point-like source (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 to the gamma-ray spectrum emitted by middle-aged pulsars and millisecond pulsars (MSPs) (Zhang & Cheng 2003; Cheng et al. 2004a). Because of the high gamma-ray luminosity observed in the 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 the GC.

Young pulsars are not likely to be a major contributor, since few supernova remnants are presently observed in the GC field targeted in deep X-ray surveys (Wang, Gotthelf & Lang 2002a; Muno et al.

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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 GC is \( \sim 10^8 M_{\odot} \) (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\(^{-1} \). We note that the rate may be increased to as high as \( \sim 1/15,000 \) yr\(^{-1} \) in this region if the star formation rate in the nuclear bulge was higher than in the Galactic field over last \( 10^8-10^9 \) yr (see Pfahl, Rappaport & Podsiałdowski 2002). Few young pulsars are likely to remain in the GC region since only a fraction (\( \sim 40 \) per cent) of young pulsars in the low-velocity component of the pulsar birth velocity distribution (Arzoumanian et al. 2002) would remain within the 20-pc region of the GC studied by Muno et al. (2003) on timescales of \( \sim 10^3 \) yr. Mature pulsars can remain active as gamma-ray pulsars up to \( 10^8 \) yr, and have the same gamma-ray power as MSPs (Zhang et al. 2004; Cheng et al. 2004a), but according to the birth rate of pulsars in the 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 GC (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 white dwarf, evolved main-sequence star or giant donor companions (Belczynski & Taam 2004, and in preparation). The current population of these MSPs may either be single (having evaporated their companion) or have remained in a binary system. Cheng, Taam & Wang (2004b) shows that wind nebulae of the MSP population in the GC region can contribute to the unidentified GC X-ray sources from the Chandra survey (Wang et al. 2002; Muno et al. 2003). Because MSPs also remain active as gamma-ray pulsars, radiating gamma-rays through the synchrotron-curvature mechanism (Cheng & Zhang 1996; Zhang & Cheng 2003), it is possible that the observed gamma-ray luminosity in the GC may be produced through an accumulation of these MSPs which would provide the observed gamma-ray spectrum.

In this paper, we will examine in detail if the MSP population could contribute to the diffuse gamma-ray spectrum in the GC region. In Section 2, we will present our motivation to consider the contribution of MSPs to diffuse gamma-rays in the GC based on the outer gap model. To find the gamma-ray spectrum of these MSPs, we assume that their globular parameters like the period and magnetic field are similar to those of the observed MSPs. In Section 3, we derive the period, magnetic field distributions of all MSPs, and MSPs in the Galactic field and in globular clusters from the present pulsar survey data base. In Section 4, we sample MSPs by a Monte Carlo method according to the different distributions, superpose their spectral profiles to fit the observed diffuse gamma-ray spectrum in the GC and obtain the number of MSPs that are needed in the GC region covered by EGRET. Our results are summarized and discussions are also presented in Section 5.

2 MOTIVATIONS

Since the masses within the region with radius \( \sim 20 \) pc (\( 17 \times 17 \) arcmin\(^2 \)) of the GC is \( \sim 10^8 M_{\odot} \) (Launhardt et al. 2002), an estimate for the fraction of MSPs in this region is about \( 10^{-3} \) of those in the entire Galaxy. Based on the population analysis of Lyne et al. (1998), the number of MSPs in the entire Galaxy may exceed \( 2 \times 10^8 \), suggesting that more than 200 MSPs exist in the GC region if their evolutionary formation channels are similar to the rest of the Galaxy. Coupled with the fact that the escape velocity from the GC is about 200 km s\(^{-1} \) and the average birth velocities of observed MSPs are \( \sim 130 \) km s\(^{-1} \) (Lyne et al. 1998), these pulsars are likely to remain in the GC through their entire lifetime. Belczynski & Taam (2004) have considered binary population synthesis in the GC region, and their results show that there exist about 300 low-mass binary systems in the GC. Furthermore, about 100–200 MSPs could be produced through the recycle scenario and lie in the GC region (\( 17 \times 17 \) arcmin\(^2 \); Taam, private communication). Recently, Pfahl & Loeb (2004) proposed that \( \sim 1000 \) radio pulsars may presently orbit Sgr A* with periods of \( \leq 100 \) yr, of which 1–10 may be detected by current radio telescopes. Therefore we believe that there should exist an MSP population in the GC, which can contribute to the high-energy emissions, e.g. X-rays and gamma-rays, which are detectable.

MSPs can remain active as gamma-ray pulsars throughout their lifetime according to outer gap models which were 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 \( f \sim 3 \times 10^7 B_{12}^{-7/4} P^{-7/4} \) (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 light cylinder radius. Then the characteristic of synchrotron-curvature radiation energy is given by (Zhang & Cheng 1997)

\[
E_{\gamma} \approx 5 \times 10^{7} f^{3/2} B_{12}^{7/4} P^{-7/4} \left( \frac{r}{R_c} \right)^{-13/8} \text{eV},
\]

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

Zhang & Cheng (1998) have studied the contribution to the Galactic diffuse gamma-rays from 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 MSPs that lie in the GC region could also contribute significantly to the diffuse gamma-ray spectrum from the GC. 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 GC.

To study the contribution of MSPs to the diffuse gamma-ray radiation from the GC in detail, e.g. fitting the spectral properties and total luminosity, we first need to derive the period and surface magnetic field distribution functions of the MSPs. Then we integrate contributions from all the MSPs 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 GC 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 MSPs from the observed pulsar data. Here, MSPs are defined as pulsars with $P < 10\text{ ms}$ and $B_{\text{surf}} < 10^{10}\text{ G}$. So we find 86 detected MSPs from the latest Australia Telescope National Facility (ATNF) Pulsar Catalog\(^1\), of which 41 MSPs are in the Galactic field, and 45 are in globular clusters. Since MSPs in the Galactic field and in globular clusters may have different properties, we derive the distribution functions of the total sample of MSPs first, and then the distribution functions of the MSPs in the Galactic field and in globular clusters separately. We should note that period derivative measurement for MSPs in globular clusters is quite difficult and uncertain, so many of them have not been given a value of surface magnetic field, and the magnetic field varies from $10^8$ to $10^{10}\text{ G}$. On the other hand, measurement for MSPs in the Galactic field is relatively accurate and reliable; the derived surface magnetic field is lower than $10^9\text{ G}$.

When fitting the normalized distribution profile, we take the Gaussian function to be of the following form:

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

To derive the period distribution function, we define $x = P$ and $1 < P < 10\text{ ms}$, and for a surface magnetic field distribution function $x = \log B_{\text{surf}}$. If the total sample of MSPs is included, the fitting parameters for the period distribution are $f_0 = 0.045$, $A = 0.60$, $W = 1.95$, $x_c = 3.91$; for the 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 are shown in Fig. 1. Just including the MSPs in the Galactic field, the parameters for the period distribution are $f_0 = 0.059$, $A = 0.48$, $W = 2.34$, $x_c = 4.28$; the parameters for the magnetic field distribution are $f_0 = -0.06$, $A = 0.24$, $W = 0.65$, $x_c = 8.40$ ($7.8 < \log B < 9$) (Fig. 2). Only including the MSPs 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 the magnetic field distribution are $f_0 = 0.04$, $A = 0.10$, $W = 0.37$, $x_c = 8.71$ ($7.8 < \log B < 10$) (Fig. 3).

\(^1\)http://www.atnf.csiro.au/research/pulsar/psrcat/
Figure 3. The distributions of the period (top) and surface magnetic field (bottom) of the detected MSPs in globular clusters. The dashed lines are the curves fitted using a Gaussian function.

4 SPECTRAL MODELLING OF DIFFUSE GAMMA-RAYS IN THE GALACTIC CENTRE

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

\[
f_m \approx 7.0 \times 10^{-2} \, p_{-3}^{26/21} \, \left( \frac{B}{10^8 \, \text{G}} \right)^{4/7} \, \delta r_{5}^{2/7},
\]

where \( \delta r \) is the distance where the local magnetic field is 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

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

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

\[
F(E_{\gamma}) = \sum_{i=1}^{n} F_i(E_{\gamma}),
\]

where \( n \) is the number of simulated MSPs with outer gaps.

During our calculations, we let the number of MSPs \( N_{\text{MSP}} \) be 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 GC region. The calculated profiles of superposed spectra of all the MSPs with outer gaps in the GC region according to three different distributions of the period and magnetic field are shown in Fig. 4. The solid line corresponds to the distributions derived from the total sample of detected MSPs; the dashed line just includes the MSPs in the Galactic field; and the dotted line just includes the MSPs in globular clusters. Our predicted spectra are consistent with the observed results, which have been analysed by Mayer-Hasselwander et al. (1998) and Hartman et al. (1999).

In Fig. 4, one can find that the predicted spectra calculated using the distributions derived from the total sample of observed MSPs and those just in globular clusters fit the observed data better. The
reduced \( \chi^2 \) values of the three curves fitted 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 MSPs in the GC will follow period and magnetic field distributions similar to the forms observed in globular clusters. However, the number of discovered MSPs 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 draw the conclusion. Meanwhile, it should be pointed out that the different profiles of predicted spectra could also be induced by the different numbers of simulated MSPs 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 no better than the solid and dotted lines in Fig. 4. After checking the simulated data, we find that according to the distributions in the field, the number fraction of simulated MSPs that 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 MSPs, i.e. \( f_{\gamma} \propto f_m^3 \). Zhang et al. (2004) considered the effect of the magnetic inclination angle in the calculation of \( f_m \), and found that \( f_m \) for large magnetic inclination angle can increase to \( 2-3 \) times the original value. MSPs generally have a large magnetic inclination angle (Ruderman 1991), then they can emit a higher gamma-ray flux, so the required number of MSPs in the region with radius \( \sim 1.5 \) to produce the diffuse gamma-rays in the GC can decrease significantly. Even considering that a proportion of MSPs have no outer gaps when \( f_m \) is larger, the simulated number of MSPs that can fit the spectra best is \( N_{\text{MSP}} \sim 1000 \) for the distributions of MSPs in globular clusters and the total sample of observed MSPs, and \( N_{\text{MSP}} \sim 2000 \) for the distributions of MSPs in the field. Probably, these decreasing numbers of MSPs in the GC are more reasonable both for the theoretical prediction and for observations.

5 DISCUSSIONS AND CONCLUSION

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

According to the period and magnetic field distributions of the observed MSPs, we sampled the global parameters (period and magnetic field) of the MSP population in the GC region by a Monte Carlo method. Since the MSPs in the Galactic field and globular clusters may have different properties, we found three classes of distributions which include the total observed sample of MSPs, just the MSPs in the field and just those in globular clusters, respectively. Then we used three possible MSP samples to calculate their gamma-ray differential spectra, and superposed the profiles to fit the observed data. The modelled results suggest that about 6000 MSPs are needed to match the observed gamma-ray spectrum. We also find that the superposed spectra of MSPs can fit the observed spectrum well except for the sample derived from the distributions of the MSPs in the field (see Fig. 4), which probably suggests that the unresolved MSPs in the GC follow distributions of period and magnetic field similar to those in globular clusters. However, because the number of MSPs in globular clusters with period and period derivative measurements is limited, and the number of MSPs in the GC is also unknown, we cannot conclude that the hypothetical millisecond population in the GC could resemble MSPs 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 MSPs for the different distribution are still required in the region of radius \( \sim 1.5 \) to fit the diffuse gamma-ray spectrum in the GC.

The multiwavelength observations have shown a complex structure in the GC region (e.g. Purcell et al. 1997; Mayer-Hasselwander et al. 1998; Wang et al. 2002a; Maeda et al. 2002), so different scenarios for the origin of the diffuse gamma-rays have been considered as mentioned in Section 1 (also see Mayer-Hasselwander et al. 1998, and references therein). Recently, Fatuzzo & Melia (2003) have attributed the GeV emission to \( \pi^0 \) decay resulting from high-energy protons interacting with the ambient matter in Sgr A East. As pointed out by Mayer-Hasselwander et al. (1998), those models cannot easily produce a very hard spectrum with a sharp turnover. In this paper, we have suggested that the spectrum turnover may be contributed by the MSP population in the GC through curvature-synchrotron radiation in the magnetosphere. The predicted spectrum of MSPs shows a cutoff above \( \sim 3 \) GeV (see Fig. 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), \( L_{\gamma, \text{TeV}} \sim 10^{33} \) erg s\(^{-1} \). These TeV photons in the 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 MSPs 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 about \( 10^{33} \) erg s\(^{-1} \), with \( (L_{\gamma, \text{TeV}}) \sim 10^{34} \) erg s\(^{-1} \), the average medium density \( n \sim 10^3 \) cm\(^{-3} \), and the magnetic field in the GC region \( B \sim 50 \) \( \mu \)G (Uchida & Güsten 1995); then the total TeV luminosity contributed by wind nebulae of MSPs is \( \sim 6 \times 10^{34} \) erg s\(^{-1} \). Compared with the present observations, we think that compact wind nebulae of MSPs through inverse Compton scattering could contribute to the TeV flux in the GC, 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 further observational constraints.

Michelson et al. (1994) have derived an upper limit to the >100 MeV luminosity of the globular cluster 47 Tuc, where over 20 MSPs 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 (\( \sim 1.2 \times 10^{35} \) erg s\(^{-1} \)) together with the estimated MSP population, the estimated gamma-ray luminosity for individual MSPs is roughly \( 6 \times 10^{32} \) erg s\(^{-1} \), which is lower than our estimate in this paper. However, Cheng & Taam (2003) have studied the X-ray properties of the MSPs in 47 Tuc, in which the average X-ray luminosity \( L_{\text{X}} \) is about a factor of 10 lower than those for typical MSPs in the field and the spectrum is dominated by a 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 47 Tuc. They suggest that the typical age of MSPs in globular clusters is much higher than for those in the field, therefore the surface magnetic field buried under
the crust during the accretion phase may diffuse back to the surface over 10^9 year time-scales. They also suggest that these complicated surface magnetic field structures can quench the outer gap because gamma-rays emitted from the polar gap can become pairs in those magnetic field lines connected with the outer gap (Ruderman & 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 the magnetic field of MSPs in 47 Tuc could be very special. In section 5 of their paper Cheng & Taam (2003) have argued that the density of stars 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. Consequently, the spin-up (or spin-down) evolution during the accretion (or post-accretion) phase of an MSP in 47 Tuc can be very much different from the evolution of other MSPs. They argue that the results of a complicated surface magnetic field structure quench the outer magnetospheric gaps as suggested by Ruderman & Cheng (1988). Therefore the low gamma-ray flux from 47 Tuc may not imply that all MSPs in globular clusters emit a weak gamma-ray flux. Secondly, if we allow the number of MSPs in the field to increase by 50 per cent, then the population of MSPs in the field can give an equally good fit as those two previous cases. Therefore we cannot conclude from the current data that the hypothetical millisecond population in the GC should resemble either MSPs in the field or MSPs in globular clusters.

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 (α) of pulsars. The first two parameters can be determined with very good accuracy; however, the last parameter is difficult to determine accurately. Zhang & 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 J2124 − 3358, they have chosen a larger inclination angle (α ∼ 40°); the model spectral breaks occur at about 3 GeV (cf. fig. 1 of Zhang & Cheng 2003). On the other hand, for PSR J0218 + 4322 and B1821 − 24 they have chosen (α ∼ 55°); the spectral breaks occur at about 10 GeV (cf. fig. 2 of Zhang & Cheng 2003). Cheng et al. (2004a) have also studied the 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 angles, whereas pulsars at medium and high Galactic latitudes 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 the gamma-ray spectral break of Galactic pulsars is higher than for those at high latitude by a factor of 3. Although there are very few confirmed gamma-ray MSPs, i.e. only three possible candidates in the EGRET catalogue at the 3σ level (Fierro 1995) and one good candidate, PSR J0218 + 4322 (Kuiper et al. 2000), we believe that high-energy satellites, like Integral and GLAST, will very soon be able to provide more information for us about the spectral behaviour of MSPs.

Finally, we are aware that the MSP population in the GC region is still an assumption at present because there have been no MSPs discovered in the inner region. We think that the assumption would be reasonable if compared with the observed MSPs in the Galaxy, especially the many MSPs discovered in systems of globular clusters, e.g. 47 Tuc (Grindlay et al. 2002), and an estimated total number of over 200 MSPs (Camilo et al. 2000). In theory, binary population synthesis in the GC region has also suggested that there are hundreds of MSPs in the GC (Belczynski & Taam 2004; Taam, private communication). However, because the electron density in the direction of the GC is very high (Cordes & Lazio 2001), it is difficult to detect MSPs with present radio telescopes. X-ray studies by Chandra and XMM–Newton of the sources in the GC would probably be a feasible method to find MSPs. Recent deep X-ray surveys of the GC 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 MSPs could contribute to a fraction of these sources, and the sources with tailed features would be good candidates. Some bright X-ray tails probably coincident with radio filaments have been suggested to be pulsar wind nebulae after image and spectral analyses (Wang, Lu & Lang 2002b; Lu, Wang & Lang 2003; Sakano et al. 2003). In summary, although still in dispute, the MSP in the GC could contribute to faint X-ray sources and diffuse gamma-rays in the GC as studied in this paper.

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