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Millisecond Pulsar Population in the Galactic Center and High Energy Contributions

W. Wang[1,2] ⋆

[1] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012
[2] Max-Planck-Institut für extraterrestrische Physik, Postfach 1312, 85741 Garching, Germany

Abstract We propose that there possibly exists a population of millisecond pulsars in the Galactic center region. Millisecond pulsars (MSPs) could emit GeV gamma-rays through synchrotron-curvature radiation as predicted by outer gap models. In the same time, the compact wind nebulae around millisecond pulsars can emit X-rays though synchrotron radiation and TeV photons through inverse Compton processes. Besides, millisecond pulsar winds provide good candidates for the electron-positrons sources in the Galactic center. Therefore, we suggest that the millisecond pulsar population could contribute to the weak unidentified Chandra X-ray sources, the diffuse gamma-rays detected by EGRET, electron-positron annihilation lines and possible TeV photons detected by HESS toward the Galactic center.

Key words: Galaxy: center — Gamma-rays: theory — X-rays: stars — pulsars: general — radiation mechanisms: non-thermal

1 MOTIVATIONS

Millisecond pulsars are old pulsars which 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. The current population of these rapidly rotating neutron stars may either be single (having evaporated its companion) or have remained in a binary system. In observations, generally millisecond pulsars have a period $< 20\,$ms, with the dipole magnetic field $< 10^{10}\,$G. According to the above criterion, we select 133 millisecond pulsars from the ATNF Pulsar Catalogue [1]. Figure 1 shows the distribution of these MSPs in our Galaxy, and they distribute in two populations: the Galactic field (1/3) and globular clusters (2/3). In the Galactic bulge region, there are four globular clusters, including the famous Terzon 5 in which 27 new millisecond pulsars were discovered (Ransom et al. 2005).

Recently, deep *Chandra* X-ray surveys of the Galactic center (GC) revealed a multitude of point X-ray sources ranging in luminosities from $\sim 10^{32} - 10^{35}$ erg s^{-1} (Wang, Gotthelf & Lang 2002a) over a field covering a 2×0.8 square degree band and from $\sim 3 \times 10^{30} - 2 \times 10^{33}$ erg s^{-1} in a deeper, but smaller field of $17' \times 17'$ (Muno et al. 2003). More than 2000 weak unidentified X-ray sources were discovered in the Muno's field. The origin of these weak unidentified sources is still in dispute. Some source candidates have been proposed: cataclysmic variables, X-ray binaries, young stars, supernova ejecta, pulsars or pulsar wind nebulae.

EGRET on board the *Compton GRO* has identified a central ($< 1^\circ$) $\sim 30\,\mathrm{MeV} - 10\,$GeV continuum source (2EG J1746–2852) with a luminosity of $\sim 10^{37}\,\mathrm{erg\,s^{-1}}$ (Mattox et al. 1996). Further analysis of the EGRET data obtained the diffuse gamma ray spectrum in the Galactic center. The photon spectrum can be well represented by a broken power law with a break energy at $\sim 2\,$GeV (see figure 2, Mayer-Hasselwander

⋆ E-mail: wwang@lamost.org
[1] http://www.atnf.csiro.au/research/pulsar/psrcat/

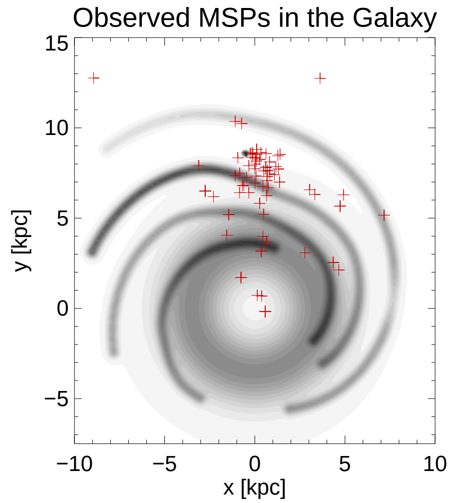

Fig. 1 The distribution of the observed millisecond pulsars in the Milky Way. The grey contour is the electron density distribution from Taylor & Cordes (1993).

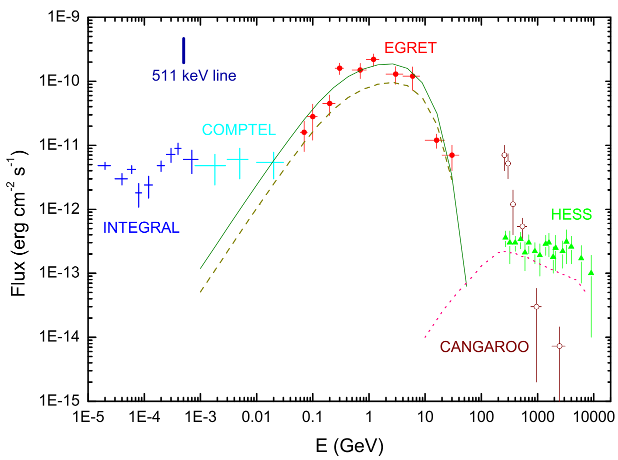

Fig. 2 The diffuse gamma-ray spectrum in the Galactic center region within 1.5° and the 511 keV line emission within 6°. The INTEGRAL and COMPTEL continuum spectra are from Strong (2005), the 511 keV line data point from Churazov et al. (2005), EGRET data points from Mayer-Hasselwander et al. (1998), HESS data points from Aharonian et al. (2004), CANGAROO data points from Tsuchiya et al. (2004). The solid and dashed lines are the simulated spectra of 6000 MSPs according to the different period and magnetic field distributions in globular clusters and the Galactic field respectively. The dotted line corresponds to the inverse Compton spectrum from MSPs.

et al. 1998). Recently, Tsuchiya et al. (2004) have detected sub-TeV gamma-ray emission from the GC using the CANGAROO-II Imaging Atmospheric Cherenkov Telescope. 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 $\Gamma = 2.21 \pm 0.19$. Some models, e.g. gamma-rays related to the massive black hole, inverse Compton scattering, and mesonic decay resulting from cosmic rays, are difficult to produce the hard gamma-ray spectrum with a sharp turnover at a few GeV. However, the gamma-ray spectrum toward the GC is similar with the gamma-ray spectrum emitted by middle-aged pulsars (e.g. Vela and Geminga) and millisecond pulsars (Zhang & Cheng 2003; Wang et al. 2005a).

So we will argue that there possibly exists a pulsar population in the Galactic center region. Firstly, normal pulsars are not likely to be a major contributor according to the following arguments. the birth rate of normal 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 $\sim 10^8\,M_\odot$ (Launhardt, Zylka & Mezger 2002), the birth rate of normal 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 $\sim 1/15000$ 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 normal pulsars are likely to remain in the Galactic center region since only a fraction ($\sim 40\%$) of normal 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 Galactic center studied by Muno et al. (2003) on timescales of $\sim 10^5$ yr. Mature pulsars can remain active as gamma-ray pulsars up to 10^6 yr, and have the same gamma-ray power with millisecond pulsars (Zhang et al. 2004; Cheng et al. 2004), 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 Galactic center (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. The current population of these millisecond pulsars may either be single or have remained in a binary system. The binary population synthesis in the GC (Taam 2005, private communication) shows more than 200 MSPs are produced through recycle scenario and stay in the Muno's region.

2 CONTRIBUTIONS TO HIGH ENERGY RADIATION IN THE GALACTIC CENTER

Millisecond pulsars could remain active as high energy sources throughout their lifetime after the birth. Thermal emissions from the polar cap of millisecond pulsars contribute to the soft X-rays ($kT < 1$ keV, Zhang & Cheng 2003). Millisecond pulsars could be gamma-ray emission source (GeV) through the synchro-curvature mechanism predicted by outer gap models (Zhang & Cheng 2003). In the same time, millisecond pulsars can have strong pulsar winds which interact with the surrounding medium and the companion stars to produce X-rays through synchrotron radiation and possible TeV photons through the inverse Compton scatterings (Wang et al. 2005b). This scenario is also supported by the Chandra observations of a millisecond pulsar PSR B1957+20 (Stappers et al. 2003). Finally, millisecond pulsars are potential positron sources which are produced through the pair cascades near the neutron star surface in the strong magnetic field (Wang et al. 2005c). Hence, if there exists a millisecond pulsar population in the GC, these unresolved MSPs will contribute to the high energy radiation observed toward the GC: unidentified weak X-ray sources; diffuse gamma-ray from GeV to TeV energy; 511 keV emission line. In this section, we will discuss these contributions separately.

2.1 Weak Unidentified Chandra X-ray Sources

More than 2000 new weak X-ray sources ($L_{\rm x} > 3 \times 10^{30}$ erg s^{-1}) have been discovered in the Muno's field (Muno et al. 2003). Since the thermal component is soft ($kT < 1$ keV) and absorbed by interstellar gas for sources at the Galactic center, we only consider the non-thermal emissions from pulsar wind nebulae are the main contributor to the X-ray sources observed by Chandra (Cheng, Taam & Wang 2006). Typically, these millisecond pulsar wind nebulae have the X-ray luminosity (2–10 keV) of $10^{30} - 10^{33}$ erg s^{-1}, with a power-law spectral photon index from 1.5–2.5.

According to a binary population synthesis in the Muno's field, about 200 MSPs are produced through the recycle scenario and stay in the region if assuming the total galactic star formation rate (SFR) of $1\,M_\odot$ yr^{-1} and the contribution of galactic center region in star formation of 0.3%. The galactic SFR may be higher than the adopted value by a factor of a few (e.g. Gilmore 2001), and the contribution of the galactic center nuclear bulge region may be also be larger than the adopted values (Pfahl et al. 2002). Then the actual number of MSPs in the region could increase to 1000 (Taam 2005, private communication). So the MSP nebulae could be a significant contributor to these unidentified weak X-ray sources in the GC. In addition, we should emphasize that some high speed millisecond pulsars (> 100 km s^{-1}) can contribute to the observed elongated X-ray features (e.g. four identified X-ray tails have $L_{\rm x} \sim 10^{32} - 10^{33}$ erg s^{-1} with the photon index $\Gamma \sim 2.0$, see Wang et al. 2002b; Lu et al. 2003; Sakano et al. 2003) which are the good pulsar wind nebula candidates.

2.2 Diffuse Gamma-rays from GeV to TeV

To study the contribution of millisecond pulsars to the diffuse gamma-ray radiation from the Galactic center, e.g. fitting the spectral properties and total luminosity, we firstly need to know the period and surface magnetic field distribution functions of the millisecond pulsars which are derived from the observed pulsar data in globular clusters and the Galactic field (Wang et al. 2005a). We assume the number of MSPs, N, in the GC within $\sim 1.5°$, each of them with an emission solid angle $\Delta\Omega \sim 1$ sr and the γ-ray beam pointing in the direction of the Earth. Then we sample the period and magnetic filed of these MSPs by the Monte Carlo method according to the observed distributions of MSPs in globular clusters and the Galactic field separately. We first calculate the fraction size of outer gaps: $f \sim 5.5P^{26/21}B_{12}^{-4/7}$. If $f < 1$, the outer gap can exist and then the MSP can emit high energy γ-rays. So we can give a superposed spectrum of N MSPs to fit the EGRET data and find about 6000 MSPs could significantly contribute to the observed GeV flux (Figure 2). The solid line corresponds to the distributions derived from globular clusters, and the dashed line from the Galactic field.

We can also calculate the inverse Compton scattering from the wind nebulae of 6000 MSPs which could contribute to the TeV spectrum toward the GC. In Figure 2, the dotted line is the inverse Compton spectrum, where we have assumed the typical parameters of MSPs, $P = 3$ ms, $B = 3 \times 10^8$ G, and in nebulae, the electron energy spectral index $p = 2.2$, the average magnetic field $\sim 3 \times 10^{-5}$ G. We predict the photon index around TeV: $\Gamma = (2 + p)/2 = 2.1$, which is consistent with the HESS spectrum, but deviates from the CANGAROO data.

2.3 511 keV Emission Line

The Spectrometer on the International Gamma-Ray Astrophysical Laboratory (SPI/INTEGRAL) detected a strong and extended positron-electron annihilation line emission in the GC. The spatial distribution of 511 keV line appears centered on the Galactic center (bulge component), with no contribution from a disk component (Teegarden et al. 2005; Knödlseder et al. 2005; Churazov et al. 2005). Churazov et al. (2005)'s analysis suggested that the positron injection rate is up to $10^{43}\ e^{+}\mathrm{s}^{-1}$ within $\sim 6°$. The SPI observations present a challenge to the present models of the origin of the galactic positrons, e.g. supernovae. Recently, Cassé et al. (2004) suggested that hypernovae (Type Ic supernovae/gamma-ray bursts) in the Galactic center may be the possible positron sources. Moreover, annihilations of light dark matter particles into $e^{\pm}$ pairs (Boehm et al. 2004) have been also proposed to be the potential origin of the 511 keV line in the GC.

It has been suggested that millisecond pulsar winds are positron sources which result from $e^{\pm}$ pair cascades near the neutron star surface in the strong magnetic field (Wang et al. 2005c). And MSPs are active near the Hubble time, so they are continuous positron injecting sources. For the typical parameters, $P = 3$ ms, $B = 3 \times 10^8$ G, the positron injection rate $\dot{N}_{e^{\pm}} \sim 5 \times 10^{37}\ \mathrm{s}^{-1}$ for a millisecond pulsar (Wang et al. 2005c). Then how many MSPs in this region? In Section 2.2, 6000 MSPs can contribute to gamma-rays with 1.5°, and the diffuse 511 keV emission have a size $\sim 6°$. We do not know the distribution of MSPs in the GC, so we just scale the number of MSPs by $6000 \times (6°/1.5°)^2 \sim 10^5$, where we assume the number density of MSPs may be distributed as $\rho_{\mathrm{MSP}} \propto r_c^{-1}$, where r_c is the scaling size of the GC. Then a total positron injection rate from the millisecond pulsar population is $\sim 5 \times 10^{42}$ e^{+} s^{-1} which is consistent with the present observational constraints. What's more, our scenario of a millisecond pulsar population as possible positron sources in the GC has some advantages to explain the diffuse morphology of 511 keV line emissions without the problem of the strong turbulent diffusion which is required to diffuse all these positrons to a few hundred pc, and predicts the line intensity distribution would follow the mass distribution of the GC, which may be tested by future high resolution observations.

3 SUMMARY

In the present paper, we propose that there exists three possible MSP populations: globular clusters; the Galactic field; the Galactic Center. The population of MSPs in the GC is still an assumption, but it seems reasonable. Importantly, the MSP population in the GC could contribute to some high energy phenomena observed by present different missions. A MSP population can contribute to the weak unidentified Chandra sources in the GC (e.g. more than 200 sources in the Muno's field), specially to the elongated X-ray features. The unresolved MSP population can significantly contribute to the diffuse gamma-rays detected by EGRET in the GC, and possibly contribute to TeV photons detected by HESS. Furthermore, MSPs in the GC or bulge could be the potential positron sources. Identification of a millisecond pulsar in the GC would be interesting and important. However, because the electron density in the direction of the GC is very high, it is difficult to detect millisecond pulsars by the present radio telescopes. At present, we just suggest that X-ray studies of the sources in the GC would probably be a feasible method to find millisecond pulsars by *Chandra* and *XMM-Newton*.

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References

Aharonian F. et al., 2004, A&A, 425, L13
Arzoumanian Z., Chernoff D. F., Cordes J. M., 2002, ApJ, 568, 289
Belczynski K., Taam R. E., 2004, ApJ, 616, 1159
Boehm C. et al., 2004, Phys. Rev. Lett., 92, 101301
Cassé M. et al., 2004, ApJ, 602, L17
Cheng K. S. et al., 2004, ApJ, 608, 418
Cheng K. S., Taam R. E., Wang W., 2006, ApJ, 641, 427
Churazov E. et al., 2005, MNRAS, 357, 1377
Gilmore G., 2001, Galaxy Disks and Disk Galaxies, eds. J.G. Funes, E.M. Corsini, San Francisco, ASP, 3
Knödlseder J. et al., 2005, A&A, 441, 513
Launhardt R., Zylka R., Mezger P. G., 2002, A&A, 384, 112
Lu F., Wang Q. D., Lang C., 2003, AJ, 126, 319
Mattox J.R. et al., 1996, ApJ, 461, 396
Mayer-Hasselwander H. A. et al., 1998, A&A, 335, 161
Muno M. P. et al., 2003, ApJ, 589, 225
Pfahl E. D., Rappaport S., Podsiadlowski P., 2002, ApJ, 571, L37
Ransom S. M. et al., 2005, Science, 307, 892
Sakano M. et al., 2003, MNRAS, 340, 747
Strong A. W., 2005, private communication
Stappers B. W. et al., 2003, Science, 299, 1372
Taylor J. H., Cordes J. M., 1993, ApJ, 411, 674
Teegarden B. J. et al., 2005, ApJ, 621, 296
Tsuchiya K. et al., 2004, ApJ, 606, L115
Wang Q. D., Gotthelf E. V., Lang C. C., 2002a, Nature, 415, 148
Wang Q. D., Lu F., Lang C., 2002b, ApJ, 581, 1148
Wang W., Jiang Z. J., Cheng K. S., 2005a, MNRAS, 358, 263
Wang W. et al., 2005b, MNRAS, 360, 646
Wang W., Pun C. S. J., Cheng K. S., 2005c, A&A, in press, astro-ph/0509760
Zhang L., Cheng K. S., 2003, A&A, 398, 639