511 keV line from millisecond pulsars in the Galactic center

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Abstract. Observations of a strong and extended positron-electron annihilation line emission in the Galactic center (GC) region by the SPI/INTEGRAL are challenging to the existing models of positron sources in the Galaxy. In this paper, we study the possibility that pulsar winds from a millisecond pulsar population in the GC might contribute significantly to the positron sources in the Galactic center region. Furthermore, since the diffusion length of positrons is short in the magnetic field, we predict that the intensity distribution of the annihilation line should follow the distribution of millisecond pulsars, which should then correlate to the mass distribution in the GC.

1. 511 keV electron-positron annihilation emission in the Galaxy

Since the first detection (Johnson & Haymes 1973) and subsequent identification (Leventhal et al. 1978) of the Galactic 511 keV annihilation line, the origin of the galactic positrons has become a lively topic of scientific debate. With the launch of the INTEGRAL gamma-ray observatory in 2002, the SPI board on telescope provides a strong constraints on the morphology and intensity of the 511 keV line emission from the Galactic center (Knödlseder et al. 2003; Jean et al. 2003). The data analyses show that the line emitting source is diffuse, and that the line flux within 5° of the GC amounts to $\sim (9.9 \pm 4) \times 10^{-4}$ photon cm$^{-2}$ s$^{-1}$ (Knödlseder et al. 2003), corresponding to a luminosity of $\sim 10^{36}$ erg s$^{-1}$. The high line luminosity requires that the positron injection rate in the GC should be around $(3 - 6) \times 10^{42}$ e$^+ s^{-1}$. Recently, analyses of the observational data by SPI/INTEGRAL with deep Galactic center region exposure show that 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), and the positron injection rate is up to $10^{43}$ e$^+ s^{-1}$ within $\sim 6^\circ$.

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 proposed to be the potential origin of the 511 keV line in the GC. Cheng et al. (2006) also propose that the continuous capture of stars by the supermassive black hole at Sgr A* could explain the morphology and intensity of the e$^\pm$ annihilation line. Here, we suggest that a population of millisecond pulsars (MSP) can significantly contribute to the 511 keV line in the GC.

2. Motivations of a millisecond pulsar population in the GC

Millisecond pulsars are old pulsars which could have been members of binary systems and then 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. Figure 1 shows the distribution of observed 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 Terzou 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 $2 \times 0.8$ square degree band and from $\sim 3 \times 10^{30} - 2 \times 10^{33}$ ergs s$^{-1}$ in a deeper, but smaller field of $17'' \times 17''$ (Muno et al.
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 ($<1^\circ$) $\sim 30\text{MeV} - 10\text{GeV}$ continuum source (2EG J1746-2852) with a luminosity of $\sim 10^{37}\text{erg s}^{-1}$ (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 $\sim 2\text{GeV}$ (see Figure 2, Mayer-Hasselwander 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. Observations of the GC with the air Cerenkov telescope HESS (Aharonian et al. 2004) also have shown a significant source centered on Sgr A* above energies of 165 GeV. 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. 2005). In Figure 2, we can see that the superposed spectrum of 6000 MSPs could significantly contribute to the observed GeV spectrum (Wang et al. 2005).

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 $\sim 10^8\text{M}_\odot$ (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 $\sim 1/150\text{ 000 yr}$. We note that the rate may be increased to as high as $\sim 1/15000\text{yr}$ in this region if the star formation rate in the nuclear bulge was higher than in the Galactic field over last $10^7 - 10^8\text{yr}$ (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 $\sim 10^5\text{yrs}$. Mature pulsars can remain active as gamma-ray pulsars up to $10^6\text{yr}$, and have the same gamma-ray power with millisecond pulsars (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. Non-thermal emissions from MSP wind nebulae can contribute to the X-ray sources observed by Chandra (Cheng, Taam, Wang 2006).

3. Millisecond pulsars as the positron sources

It is well known that relativistic particles from pulsar winds interacting with the interstellar medium form the synchrotron wind nebulae. Chi, Cheng, & Young (1996) proposed that the bulk of the cosmic positrons could originate from pulsar winds. In this work, we consider that the electron-positron pair production occurs in the pulsar outer-magnetospheric region.

It has been proposed that there is a strong multipole magnetic field near the stellar surface, although a global dipole magnetic field gives a good description of the magnetic field far from the star (Ruderman & Sutherland 1975; Ruderman 1991). The typical radius of curvature $l$ of the local magnetic field is on the order of the crust thickness.
of the star (i.e. \( l \sim 10^5 \) cm), which is much less than the dipole radius of curvature of dipole field component near stellar surface. The relation between the local multipole magnetic field and dipole field can be given by (Zhang & Cheng 2003)

\[
B_s \approx B_d \left( \frac{R}{l} \right)^3, \tag{1}
\]

where \( B_d \) is the dipole magnetic field of a pulsar, \( R \) is the radius of neutron stars. For MSPs, typically \( B_d \sim 10^8 - 10^9 \) G, \( B_s \sim 10^{11} - 10^{12} \) G which is much lower than the quantum critical magnetic field \( B_{\text{crit}} \sim 4.4 \times 10^{13} \) G, so pair cascades are also efficient in the local multipole field.

The pair production mechanism is a synchrotron photon cascade in a strong magnetic field. Photons will be converted into \( e^\pm \) pairs in the local magnetic field when their energy satisfies (Ruderman & Sutherland 1975)

\[
E \geq E_{\text{crit}} = \frac{2m_e c^2}{15} \frac{B_d}{B_d} \left( \frac{R}{l} \right)^{-3}. \tag{2}
\]

The primary \( e^\pm \) from the outer-gap have the energy \( E_p = \gamma_p m_e c^2 = 5.7 \times 10^{12} \) P1/3 eV, so generally, the energies of primary curvature photons and secondary synchrotron photons are higher than \( E_{\text{crit}} \), a photon-electron cascade will start and develop until this condition fails. At the end of a cascade, each incoming primary electron-positron can produce, on average,

\[
N_{e^\pm} = \frac{E_p}{E_{\text{crit}}} = 1.9 \times 10^3 B_{d,9} P^{1/3} \left( \frac{R}{l} \right)^3, \tag{3}
\]

and then the total pair production rate can be estimated as

\[
\dot{N}_{e^\pm} = f \dot{N} N_{e^\pm} = 2 \times 10^{33} f B_{d,9}^{10/7} P^{-8/21} \left( \frac{R}{l} \right)^{30/7} \text{s}^{-1}, \tag{4}
\]

where \( f \approx 5.5 P^{26/21} B_{d,9}^{-4/7} \) is the fraction size of the outer gap, and

\[
\dot{N} = 2.7 \times 10^{27} P^{-2} B_{d,9} \left( \frac{R}{l} \right)^3 \text{s}^{-1} \tag{5}
\]

is the primary electron-positrons passing through the polar gap (Goldreich & Julian 1969). Taking the typical parameters \( P = 3 \) ms, \( B_d = 3 \times 10^8 \) G, the positron injection rate for a MSP: \( \dot{N}_{e^\pm} \sim 5 \times 10^{37} \text{e}^+ \text{s}^{-1} \) (Wang et al. 2006).

Since these pairs are created close to the stellar surface and the field lines are converging, only a small fraction may keep moving toward the star and annihilate on the stellar surface. Ho (1986) showed that the loss cone for these pairs will approach \( \pi/2 \), in other words, most pairs will be reflected by the magnetic mirroring effect and then move toward the light cylinder. These particles will flow out with the pulsar wind and be accelerated by the low-frequency electro-magnetic wave.

**Then how many MSPs in the region of annihilation emissions?** Figure 2 has shown that 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 \( \times (6°/1.5°)^2 \sim 10^3 \), where we assume the number density of MSPs may be distributed as \( \rho_{\text{MSP}} \propto r_e^{-1} \), where \( r_e \) is the scaling size of the GC. Then a total positron injection rate from the millisecond pulsar population is \( 5 \times 10^{42} \) 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.

### 4. Discussions and conclusion

In the present work, we suggest 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 millisecond pulsar population in the Galactic center could provide the major sources of positrons. In addition, the scenario of a MSP population in the GC can reasonably explain the diffuse morphology of 511 keV line emissions.

Since there are many possible positron sources at present as noted in §1. Thus, how could we distinguish the model of a millisecond pulsar population from other models? Firstly, we can estimate the typical spatial diffusion scale of positrons in the magnetic field of the GC,
which is given by \( \lambda_{\text{diff}} \sim (r_L c t)^{1/2} \) (Wang et al. 2006), where \( r_L \approx E_e/eB \) is the Larmor radius, \( E_e \) is the energy of positrons, \( B \sim 10^{-5} \) G is the average magnetic field in the GC (LaRosa et al. 2005). The average cooling time \( t \) of positrons in the GC is \( \sim 10^6 \) years, so the characteristic diffusion scale is about 1 pc. Because of the low angular resolution of SPI/INTEGRAL (about 2 degrees), we can assume that the positrons annihilate in the local region as their sources, i.e. the millisecond pulsars.

Therefore, we predict that the spatial intensity distribution of the annihilation lines should follow the spatial distribution of MSPs if a millisecond population exists in the GC. We could assume the spatial distribution of MSPs should follow the mass distribution of the GC though we do not know how well they follow each other. But because the proper motion velocity of MSPs is relatively low, we could reasonably assume that the two distributions are quite close to each other. Then if the positron sources originate in the MSP population, the 511 keV annihilation line intensity would follow the mass (e.g. stars) distribution of the Galactic center region. If the positrons originate from supernovae or hypernovae, the 511 keV line emission could follow the distribution of massive stars and dense molecular clouds. For the light dark matter scenario, the annihilation emissions may correlate to the dark matter density profile. Discrimination of these possible correlations may be tested in the future high resolution observations.

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