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Gamma-ray Mature Pulsars: Unidentified EGRET Sources, Possible TeV Sources and Radio Detectivity

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Abstract We study the γ-ray emission from the pulsar magnetosphere based on outer gap models, and the TeV radiation from pulsar wind nebulae (PWNe) through inverse Compton scattering using a one-zone model. We carry out Monte Carlo simulations of γ-ray pulsars in the Galaxy and the Gould Belt, assuming values for the pulsar birth rate, initial position, proper motion velocity, period, and magnetic field distribution and evolution based on observational statistics. We select from the simulation a sample of 44 mature pulsars in the Galactic plane ($|b| \leq 5^\circ$) and a sample of 32 mature pulsars at high latitudes ($|b| > 5^\circ$) which could be detected by EGRET. About 12 mature pulsar could be observed in the radio band. The results showed that GeV radiation from the magnetosphere of mature pulsars can contribute to the high latitude unidentified EGRET sources. The TeV fluxes from the pulsar wind nebulae of our simulated sample produced through inverse Compton scattering by relativistic electrons on the cosmic microwave background and synchrotron seed photons are calculated. We suggest that strong EGRET sources may be potential TeV source candidates, and up to 15 sources could be detected by present and future three-generation TeV telescopes if they are mature pulsars.

Key words: radiation mechanisms: nonthermal — stars: neutron — pulsars: general — γ-rays

1 INTRODUCTION

There are about 170 unidentified γ-ray sources in the third EGRET catalog, and nearly one third of these sources lie close to the Galactic plane $|b| < 5^\circ$ (Hartman et al. 1999). Most of those unidentified sources in the Galactic plane can be identified as γ-ray pulsars, possibly Geminga-like pulsars which are radio quiet (Cheng & Zhang 1998; Zhang, Zhang & Cheng 2000). For the medium and high latitude sources, it has been suggested that some of them are associated with the supernova remnants in the nearby Gould Belt (Gehrels et al. 2000; Grenier 2000). In addition, Harding & Zhang (2001) used the polar cap model to investigate if γ-ray pulsars viewed at a large angle to the neutron star magnetic pole could contribute to unidentified EGRET sources in the medium latitudes associated with the Gould Belt.

At the same time, these γ-ray pulsars could produce wind nebulae through the interactions between relativistic wind particles with the interstellar medium (ISM). The pulsar wind nebulae will contribute to the production of non-pulsed X-ray emission by synchrotron processes (Chevalier 2000; Cheng, Taam & Wang 2004b), and TeV photons through inverse Compton scattering (ICS)(Aharonian, Atoyan & Kifune 1997). These excess TeV photons have been detected in some known pulsar wind nebulae, such as the Crab, Vela, and B1259–63 (Kifune et al. 1995; Yoshikoshi et al. 1997; Aharonian et al. 2005b). The observed X-ray luminosity of the known nebulae are well consistent with the predicted one by our model (see Fig. 1).

It has been shown that GeV photons can be produced in the pulsar magnetosphere in outer gap models (Cheng et al. 1986; Zhang & Cheng 1997). A revised outer gap model (Zhang et al. 2004) takes into account

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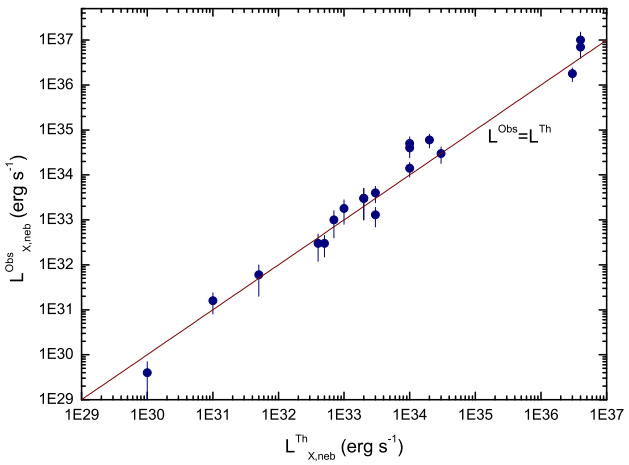

Fig. 1 The comparison between the observed X-ray luminosity (2–10 keV) of the pulsar wind nebulae and predicted luminosity by the one-zone model.

the effect of the inclination angle α between the magnetic axis and the rotational axis, which can determine the gap size of the outer gap. This allows some pulsars with appropriate combinations of α, P and B, to maintain the outer gap for at least $\sim 10^6$ years. Their advanced ages allow these pulsars enough time to move up to high Galactic latitudes as weak γ-ray sources. This leads us to propose that mature γ-ray pulsars with ages $\sim 10^5 - 10^6$ years can contribute to the unidentified EGRET sources (Cheng et al. 2004a; Wang et al. 2005). These mature pulsars also remain active in producing relativistic wind particles, and form compact wind nebulae. In addition, TeV photons can be created in the nebulae through the ICS process (Wang et al. 2005). We apply a statistical approach using Monte Carlo simulation to study the Unidentified Gamma-ray EGRET Sources. First we will simulate the galactic pulsar population and use the outer gap model to calculate the MeV-GeV photon power from these simulated pulsars. We have ignored the contribution from the polar gap for simplicity. We can determine which simulated pulsars can be detected by EGRET in γ-rays; we call them γ-ray loud pulsars. The next step is to calculate the γ-ray emission from pulsar wind nebulae based on the simulated pulsar parameters. We should point out that the distribution of γ-ray loud pulsars is model dependent. Subsequently we study the TeV γ-rays emitted from the pulsar winds when they interact with their ambient interstellar medium. We argue that strong EGRET sources may be potential TeV source candidates for current and future TeV telescopes.

2 SIMULATION OF GAMMA-RAY PULSARS IN THE GALAXY

We carry out a Monte Carlo simulation of the Galactic pulsars born during the past 10 Myr in the Galaxy and the Gould Belt (Wang et al. 2005). The detailed Monte Carlo assumption and steps can be found in Cheng & Zhang (1998) or Wang et al. (2005). We find a total of 76 γ-ray mature pulsars of ages larger than 10^5 years that could be detected by EGRET. Out of this simulated sample, 44 of them lie in the Galactic plane ($|b| \leq 5^\circ$) and 32 lie at higher latitudes ($|b| > 5^\circ$). Currently, four radio pulsars with age $> 10^5$ yrs are identified as γ-ray pulsars, i.e. Geminga, PSR B1055–52, PSR B1951+32, PSR J0218+42 (Thompson et al. 1996; Kuiper et al. 2000). The predicted γ-ray pulsar numbers appear very much larger than the confirmed γ-ray pulsars. We should notice that first, not all 76 predicted are radio-loud. The radio beaming factor is roughly 0.15 (Biggs 1990). Taking the radio beaming factor into account, we predict that $\sim$12 EGRET Unidentified Sources will be identified in the radio band in future.

The TeV flux distribution of the mature pulsars at high latitudes, $|b| > 5^\circ$ (solid histogram) and on the Galactic plane, $|b| \leq 5^\circ$ (dashed histogram), are presented in Figure 2. The predicted TeV fluxes of our low

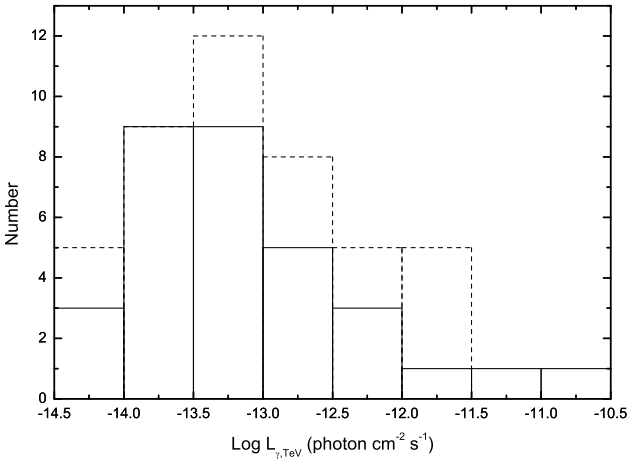

Fig. 2 The distribution of the TeV flux from the wind nebulae of the simulated γ-ray pulsars which could be the unidentified EGRET sources. The distributions of the pulsars in the high latitude ($|b| > 5^\circ$) (solid), and in the Galactic disk ($|b| \leq 5^\circ$) (dashed) are shown.

latitude simulated sample are all lower than 3×10^{-12} photon cm^{-2} s^{-1}, which is also the upper flux limit of all but two of the high latitude sample. The predicted TeV flux from our sample is lower than the present observational constraints, but with the rapid advancements of the ground-based TeV telescopes, some of the unidentified EGRET sources could be identified as TeV sources. For example, HESS is an imaging telescope array system with an array of four imaging atmospheric Cherenkov telescopes (Hinton 2004). Now it is fully operational, and its expected sensitivity at 1 TeV is about 2×10^{-13} photon cm^{-2} s^{-1}, then we also expect HESS could possibly detect TeV photons from about 15 unidentified EGRET sources if they are mature pulsars.

3 SUMMARY AND DISCUSSION

We would like to summarize our results as follows:

(1) GeV radiation mainly comes from the pulsar magnetosphere as predicted by outer gap models, and gamma-ray pulsars may contribute a good fraction of unidentified EGRET sources both in galactic plane as well as in high latitudes;
(2) About 12 unidentified EGRET sources could be detected in the radio band in the future;
(3) Unidentified EGRET sources associated with pulsars may have pulsar wind nebulae, and a one-zone model can describe their X-ray properties by synchrotron radiation and TeV photons through inverse Compton processes;
(4) Unidentified EGRET sources associated with pulsar wind nebulae could be detected in TeV band by the present and future ground based telescopes, in particular those sources either in high latitudes or stronger EGRET sources. About 15 unidentified EGRET sources could be detected by HESS if they are pulsars. Recently, A first sensitive survey of the inner part of the Milk Way with HESS discovered 8 new TeV sources along the Galactic plane (Aharonian et al. 2005a). Among these sources, 5 sources may be associated with known pulsars, and 2 sources might associate with unidentified EGRET sources. So we believe in future more and more TeV sources in the Milk Way will be detected, and pulsar wind nebulae will be the potential contributors to this new high energy gamma-ray source population.

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