TESTING THE MILLISECOND PULSAR SCENARIO OF THE GALACTIC CENTER GAMMA-RAY EXCESS WITH VERY HIGH ENERGY GAMMA-RAYS

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ABSTRACT

Recent analyses of Fermi Large Area Telescope data show an extended GeV γ-ray excess on top of the expected diffuse background in the Galactic center region, which can be explained by annihilating dark matter (DM) or a population of millisecond pulsars (MSPs). We propose observations of very high energy (VHE) γ-rays to distinguish the MSP scenario from the DM scenario. GeV γ-ray MSPs should release most of their energy to the relativistic e± wind, which will diffuse into the Galaxy and radiate TeV γ-rays through inverse Compton scattering and bremsstrahlung processes. By calculating the spectrum and spatial distribution, we show that such emission is detectable with the next generation VHE γ-ray observatory, the Cherenkov Telescope Array (CTA), under reasonable model parameters. It is essential to search for multi-wavelength counterparts to the GeV γ-ray excess in order to solve this mystery in the high-energy universe.

Key words: cosmic rays – gamma rays: ISM – pulsars: general – radiation mechanisms: non-thermal

1. INTRODUCTION

Observations of high-energy γ-rays from the Galactic center (GC) have revealed very interesting features at different scales. The atmospheric imaging Cherenkov telescope, High Energy Stereoscopic System (HESS), has discovered a point-like source4 that may have originated from the central supermassive black hole (Aharonian et al. 2004) as well as an extended source from the ridge which could be explained through the interaction of a fresh cosmic ray (CR) source with the interstellar medium (ISM; Aharonian et al. 2006). Analyses of the data from the space-borne γ-ray detector Fermi Large Area Telescope (Fermi-LAT) have also revealed corresponding point-like (Chernyakova et al. 2011) and ridge emission (Yusef-Zadeh et al. 2013; Macias & Gordon 2014). Moreover, an even more extended, circular γ-ray excess on top of the central point and ridge emission has been identified in the Fermi-LAT data by quite a few groups (Goodenough & Hooper 2009; Vitale & Morselli 2009; Boyarsky et al. 2011; Hooper & Goodenough 2011; Abazajian & Kaplinghat 2012; Gordon & Macias 2013; Hooper & Slatyer 2013; Huang et al. 2013; Abazajian et al. 2014a; Calore et al. 2014a; Daylan et al. 2014; Fermi-LAT collaboration 2014; Zhou et al. 2014).

Finally, a bubble structure on the Galactic scale has also been shown in Fermi-LAT data (Dobler et al. 2010; Su et al. 2010; Su & Finkbeiner 2012; Ackermann et al. 2014; Yang et al. 2014). These multi-scale, wide-band features have very interesting implications for GC activity and stellar history (Crocker et al. 2011; Crocker 2012).

The circularly symmetric γ-ray excess is of special interest as it may be connected to the emission from dark matter (DM) annihilation in the GC (Goodenough & Hooper 2009; Hooper & Goodenough 2011; Abazajian & Kaplinghat 2012; Gordon & Macias 2013; Abazajian et al. 2014a; Daylan et al. 2014; Hagiwara et al. 2014). The deprojected spatial distribution of the γ-ray source follows approximately θ2.4, with θ being the angle away from the GC, which seems to be consistent with DM annihilation with a generalized Navarro–Frenk–White (gNFW, Zhao 1996; Navarro et al. 1997) density profile. The energy spectrum peaks at several GeV and can be well fit by the scenario of DM annihilation into a pair of quarks or τ leptons with mass of DM particles of 10 s GeV2 (Hooper & Goodenough 2011; Abazajian & Kaplinghat 2012; Gordon & Macias 2013). Nevertheless, astrophysical scenarios such as a population of unresolved millisecond pulsars5 (MSPs, Wang et al. 2005; Abazajian 2011; Mirabal 2013; Calore et al. 2014b; Yuan & Zhang 2014), as well as CR interactions in the GC, may also account for this γ-ray excess (Carlson & Pro-fumo 2014; Petrović et al. 2014). On the other hand, there seems to be tension between other observations of CRs and radio emission and the DM annihilation scenario, although they still suffer from uncertainties (Bringmann et al. 2014; Cirigli et al. 2014; Hooper et al. 2014). The origin of the γ-ray excess is still in debate, and we may need future, multi-wavelength observations to test different models.

The MSP scenario is favored for several reasons. The spectrum of the GeV γ-ray excess is very similar to those observed for MSPs (Abdo et al. 2013) and for some globular clusters (Abdo et al. 2010). MSPs are old enough to extend to relatively large scales, which may possibly explain the large extension of GeV γ-ray excess (Daylan et al. 2014). The observed distribution of Galactic low-mass X-ray binaries (Revnivtsev et al. 2008), the progenitors of MSPs, follows the θ2.4 profile as observed for the γ-ray signal (Yuan & Zhang 2014). If there is a population of unresolved γ-ray MSPs in the Galactic bulge to contribute to the γ-ray excess, then one would naturally expect that a portion (probably most) of the spin-down energy should be carried by the relativistic e± winds from those pulsars. Such wind e± may further be accelerated up to very high energies (VHEs; TeV energies) in the shocks produced by pulsar winds (Bednarek & Sitarek 2007; Bednarek & Sobczak 2013). These leptons will

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4 See Kosack et al. (2004) for an earlier potential detection of this source with significance ~3.7σ by Whipple.

5 See, however, Hooper et al. (2013) and Cholis et al. (2014).
then diffuse into the ISM in the Galaxy and radiate through inverse Compton scattering (ICS), bremsstrahlung, and synchrotron emission. Since the $e^\pm$ wind generally dominates the energy budget over the GeV $\gamma$-rays from pulsars, we should investigate such emission from $e^\pm$. Future observations of VHE $\gamma$-rays from the GC region, e.g., by the Cherenkov Telescope Array (CTA; Acharya et al. 2013), could test the MSP scenario of the Fermi GeV $\gamma$-ray excess, and may distinguish it from the DM scenario (Abazajian et al. 2014b; Lacroix et al. 2014).

In this work, we explore the VHE $\gamma$-ray emission associated with relativistic $e^\pm$ winds from GC MSPs, using the Fermi $\gamma$-ray excess as a normalization of the MSP population. In Section 2, we briefly describe the $e^\pm$ production model of MSPs. The major results for the VHE $\gamma$-ray emission from the MSP $e^\pm$ and its detectability with CTA will be presented in Section 3. We conclude and discuss our results in Section 4.

2. $e^\pm$ FROM MSPS

It has been well established that rotation-powered pulsars release most of their rotational energy as a relativistic wind of magnetized $e^\pm$ plasma from the magnetosphere (Rees & Gunn 1974). The interaction of such a wind with the ISM will then form a shock which can also accelerate the $e^\pm$ to VHE. The synchrotron or ICS emission from these $e^\pm$ form the so-called pulsar wind nebula (PWN).

Assuming that the pulsar spin-down power is predominately carried away by the kinetic energy of the wind particles, one obtains (Kennel & Coroniti 1984a, 1984b)

$$L_{sd} = \gamma_e N_{GJ} m_e c^2 \kappa (1 + \sigma)/f_{e^\pm},$$

where $L_{sd}$ is the spin-down power of the pulsar, $\gamma_e$ is the Lorentz factor of the wind particles, $N_{GJ}$ is the Goldreich–Julian current (Goldreich & Julian 1969), $m_e$ is the electron mass, $c$ is the speed of light, $\kappa$ is the $e^\pm$ pair multiplicity, $\sigma$ is the magnetization parameter (the ratio of the Poynting flux to the kinetic energy flux), and $f_{e^\pm}$ is the relative energy fraction carried by $e^\pm$ particles. For typical parameters of MSPs, the Lorentz factor of the wind particles can be derived as (Cheng et al. 2006, 2010)

$$\gamma_e = 4 \times 10^3 (f_{e^\pm}/\kappa_3)^{-1/3},$$

where $L_{sd}$ is the spin-down power in units of $10^{34} \text{ erg s}^{-1}$ and $\kappa_3 = \pi/10^3$. The spin-down power carried away by the $e^\pm$ pairs is simply $L_{e^\pm} = f_{e^\pm} L_{sd}$. Typically, we will have $f_{e^\pm} \simeq 1$. The energy distribution of the wind $e^\pm$ could be relativistic Maxwellian (Aharonian et al. 2012). For simplicity, we adopt monochromatic injection of the wind $e^\pm$ for this case without considering possible acceleration or cooling in the PWN (see below).

The pulsar winds may be further accelerated if a shock region exists (Bednarek & Sitarek 2007; Bednarek & Sobczak 2013). In the GC stellar cluster, the maximum achievable energy of the $e^\pm$ can be as high as 50 TeV (Bednarek & Sobczak 2013). The fraction of accelerated $e^\pm$ and the final spectrum of the accelerated $e^\pm$ are not clear. We may simply assume a power-law spectrum with an exponential cutoff at maximum energy (Bednarek & Sobczak 2013). The total power of the accelerated $e^\pm$ can be absorbed in the efficiency $f_{e^\pm}$.

### Table 1

| Spectrum | $E_{inj}$ | $\alpha$ | $E_{max}$ | $f_{e^\pm}$ |
|----------|-----------|----------|-----------|-------------|
| $E^{-\alpha}$ | 200 | ... | ... | 0.9 or 0.1 |
| $E^{-\alpha}$ | 20 | ... | ... | 0.9 or 0.1 |
| $E^{-\alpha} \exp (-E/E_{max})$ | 2.0 | $5 \times 10^{4}$ | 0.9 or 0.1 |

Finally, $e^\pm$ may radiate and lose energy inside the PWN. For young pulsars (e.g., Crab), most of the spin-down energy is released through synchrotron radiation in the nebula. However, this may not be the case for MSPs since they are generally old and their PWNe are so extended that the magnetic field is weak (Kashiyama et al. 2011; Kisaka & Kawamaka 2012). Therefore we assume that a fraction of the $e^\pm$ can escape from the PWN into the Galaxy’s ISM, and we absorb this fraction in the efficiency $f_{e^\pm}$.

As for the spatial distribution of the $e^\pm$ injection, we adopt the result inferred from the $\gamma$-ray excess, i.e., a spherical power-law distribution $r^{-\gamma}$ that extends to $\sim 1.5 \text{ kpc}$ ($\sim 10^5$; Hooper & Goodenough 2011; Abazajian & Kaplinghat 2012; Gordon & Macias 2013; Daylan et al. 2014). The $\gamma$-ray emission ($e^\pm$ source) may extend to even larger scales (Daylan et al. 2014; Zhou et al. 2014). However, it will not significantly affect the results of the current study which focuses on the GC region.

In summary, we will discuss either monochromatic or power-law injection of $e^\pm$ in the extended region around the GC, which represents the scenario without or with acceleration in pulsar wind shocks, respectively. The canonical model parameters of $e^\pm$ are tabulated in Table 1. Furthermore, we assume that the typical $\gamma$-ray efficiency with respect to the spin-down power is 0.1 (Abdo et al. 2013). Thus we obtain $L_{e^\pm} = f_{e^\pm} L_{sd} = 10f_{e^\pm} \gamma_e$.

3. VHE $\gamma$-RAY EMISSION OF GC MSPS

Given the above source injection of relativistic $e^\pm$, we use the GALPROP$^6$ numerical tool (Moskalenko & Strong 1998; Strong & Moskalenko 1998) to calculate the propagation of $e^\pm$ as well as the secondary $\gamma$-ray emission through ICS and bremsstrahlung. We use the default magnetic field in GALPROP, which is about 5 $\mu$G in the GC. Thus the synchrotron energy loss of $e^\pm$ is less important compared to the ICS energy loss given the very strong optical radiation in the GC ($\sim 10^5 \text{eV cm}^{-2}$; Moskalenko et al. 2006). The diffusion with reacceleration configuration of the propagation model is adopted. Three groups of propagation parameters are adopted with the characteristic height of the propagation halo, $z_{hp}$, varying from 2 to 10 kpc (Ackermann et al. 2012). Such a range will largely cover the uncertainties of the propagation parameters (Trotta et al. 2011; Jin et al. 2014). The propagation parameters are provided in Table 2.

The calculated ICS and bremsstrahlung spectra from the propagated $e^\pm$ produced by the MSPs in the $7\arcmin \times 7\arcmin$ region around the GC are shown in Figures 1 and 2 for monochromatic injection and power-law injection, respectively. The Fermi-LAT data of the $\gamma$-ray excess (Gordon & Macías 2013), together with the direct $\gamma$-ray emission expected from a

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$^6$ http://galprop.stanford.edu/
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Table 2
Cosmic Ray Propagation Parameters

| D0 (10^28 cm^2 s^-1) | z0 (kpc) | vA (km s^-1) | δ |
|----------------------|----------|-------------|---|
| 1                    | 2.7      | 35.0        | 0.33 |
| 2                    | 5.3      | 33.5        | 0.33 |
| 3                    | 9.4      | 28.6        | 0.33 |

Note. The columns from left to right are the diffusion coefficient D0 at the reference rigidity R = 4 GV, the height of the propagation halo z0, the alfven speed vA, and the power-law index δ of the rigidity dependence of the diffusion coefficient.

The result shows that there is indeed a VHE component, mainly from the ICS off the starlight, if the injection energies of e^± are sufficiently high. For the monochromatic injection case with E_{inj} = 20 GeV, the ICS emission falls in the same energy window of the current GC excess. It may contribute partially to the observed signal. However, the spatial morphology of this ICS component should be different from the direct γ-ray emission from MSPs (see Figure 4). For the E_{inj} = 200 GeV case, if f_{e^\pm} = 0.9, then the ICS emission will exceed the Fermi-LAT data above several GeV. This may indicate that the e^± efficiency may not be as high as ~1, or otherwise such a high-energy tail is missed in the Fermi-LAT data analysis because of the different morphology. There is a bump in the γ-ray emission at 10–200 GeV corresponding to E_{inj} = 200 GeV which might be detectable by future VHE observations. For the power-law injection model, the spectrum of the VHE component is shallower and can probably extend to much higher energies.

In order to have a rough idea of the detectability of this VHE emission, we compare it with the HESS-detected diffuse ridge emission integrated in the region |l| < 0°8, |b| < 0°3 in Figures 1 and 2 (Aharonian et al. 2006). The VHE component from the MSPs could be comparable to or even brighter than the ridge emission, although it is more extended. Given the much better sensitivity of future VHE experiments such as CTA, it should be possible to detect such a bright source (Acharya et al. 2013).

Due to the extension of the emission, the nearly isotropic electron background will contaminate the detection. The spectrum of the total e^± based on AMS-02 (Aguilar et al. 2014) and HESS (Aharonian et al. 2008) measurements is also shown by the gray line in Figures 1 and 2. We can see that for the power-law injection scenario with a large value of f_{e^\pm}, the ICS emission may exceed the electron background for energies higher than several TeV (the left panel of Figure 2). However, in general, the electron background is much higher than the expected γ-ray signal. Therefore, the spatial morphology may be necessary to subtract the electron background.

Figure 3 shows the morphology of the ICS (top panels) and bremsstrahlung (bottom panels) emission for the power-law injection scenario. From left to right, we show the results at 0.11, 33.9, and 980 GeV, respectively. The ICS emission is almost symmetric around the GC and shows a decrease beyond ~2°. The morphology becomes more concentrated with increasing energy, which is expected due to the more significant cooling of higher-energy e^±. The morphological study of the Fermi-LAT γ-ray excess shows that the signal is pretty symmetric with the axis ratio, departing from unity less than 20% (Daylan et al. 2014). However, the current Fermi-LAT data may not be able to exclude a slightly asymmetric morphology. The CTA, on the other hand, may determine more precisely the morphology of this signal if the flux is high. We should keep in mind that there are more complexities concerning the very detailed morphology of the ICS emission caused by particle diffusion and the distribution of the background radiation field. The bremsstrahlung emission is strongly correlated with the gas distribution, and is more concentrated in the Galactic plane. This may be contaminated by the diffuse γ-ray background from Galactic CRs. As we have seen before, ICS emission will generally dominate bremsstrahlung. Therefore, the nearly symmetric ICS component of the VHE emission is an important expectation of the MSP model to explain the Fermi-LAT GC excess. The morphology of the ICS emission will be crucial to eliminate the electron background.

For comparison, in Figure 4, we show the sky-map of the ICS emission integrated in the 1–10 GeV range and the contours of the observed Fermi-LAT GeV γ-ray excess (Figure 4 of Gordon & Macías 2013). The model parameters to calculate the ICS emission are the same as those in Figure 3, and the flux levels of the contours of Fermi-LAT data are 0.8, 0.6, 0.4, and 0.2 from the inside to the outside. The result does show that the direct emission from the MSPs is much more concentrated than the ICS emission.

Finally, we provide the surface brightness distribution of the ICS emission above 0.1 TeV in Figure 5. The propagation parameters are the second ones in Table 2. We adopt the efficiency f_{e^\pm} = 0.9 for both the monochromatic and power-law injection scenarios, and E_{inj} = 200 GeV for the monochromatic injection scenario. The surface brightness decreases with increasing θ angle away from the GC. The rough behavior beyond 1° is ~θ^-0.9, which is shallower than that for the Fermi-LAT excess. This is mainly due to the diffusion of e^±. The HESS observation of the GC ridge emission, calculated from the fitting spectrum 1.73 × 10^{-5} (E/TeV)^{-2.25} TeV^{-1} cm^{-2} s^{-1} sr^{-1} (Aharonian et al. 2006), is shown by the short dashed line. The ICS emission seems to be fainter than the ridge emission. Since the sensitivity of CTA will be better by an order of magnitude than HESS, it is possible for CTA to identify such a VHE γ-ray component.

4. CONCLUSION AND DISCUSSION

The recent discovery of the GeV γ-ray excess from the GC in Fermi-LAT data has triggered extensive discussions of the DM origin or astrophysical origins, such as MSPs. It is very essential to investigate the possible effects on future observations which may test different models. For the MSP scenario, it is expected that the wind e^±, with very high Lorentz factor (~10^8), will carry most of the pulsar spin-down energy and may diffuse and radiate in the vicinity of the GC. The ICS and bremsstrahlung emission from the wind e^± may be detectable by VHE γ-ray experiments such as CTA.

We find that there could be a bright VHE component from the wind e^±, mainly from the ICS off the interstellar radiation field, for a variety of model parameters. This ICS emission is nearly spherically symmetric within several degrees of the GC. The spectrum depends on the assumption of e^± injection and can likely extend to higher than 100 GeV for reasonable model parameters. The ICS emission has larger total flux than the
Galactic ridge emission observed by HESS (Aharonian et al. 2006), although the former is more extended than the latter and may be detectable with CTA. The detection of a VHE counterpart of the GeV γ-ray excess will provide strong support for the MSP (or other similar astrophysical) scenario to explain the GeV γ-ray excess compared to the DM annihilation scenario.

The detailed detectability of the VHE source with CTA relies on detector performance and background rejection techniques for extended source analysis. These will be interesting future works. Through a rough comparison with the HESS data of the GC ridge and the improvement of the sensitivity of CTA compared with HESS, it should be promising for CTA to detect such VHE emission.

We should note that the globular clusters, which are thought to be rich of MSPs, have been shown to be a class of γ-ray sources by Fermi-LAT (Abdo et al. 2010). Similar to the scenario discussed in this work, the VHE γ-ray emission from the ICS of the wind $e^\pm$ is expected from the globular clusters (Bednarek & Sitarek 2007; Venter et al. 2009; Cheng et al. 2010). HESS has discovered the VHE γ-ray emission from the direction of globular cluster Terzan 5 (Abramowski et al. 2011), and set an upper limit for 47 Tucanae (Aharonian et al. 2009). The detectability of globular clusters with CTA has been investigated in detail in de Oña-Wilhelmi et al. (2013). Here we just check the consistency of the model prediction with the current observations. We take the power-law model as an illustration since the threshold energies of the HESS observations are relatively high (a few hundred GeV).

Furthermore we adopt $\xi = 0.9$ to give a maximum estimate. Assuming the ratio between the ICS component and the direct emission from MSPs for the globular clusters is the same as the GC excess discussed in this work, we find that the predicted VHE γ-ray flux is $I(>440\text{ GeV}) \approx 2.9 \times 10^{-12}\text{ cm}^{-2}\text{s}^{-1}$ for Terzan 5 and $I(>800\text{ GeV}) \approx 4.4 \times 10^{-13}\text{ cm}^{-2}\text{s}^{-1}$ for 47 Tucanae, based on the Fermi-LAT fluxes (Abdo et al. 2010). For comparison, the HESS observations provide $I(>440\text{ GeV}) = (1.2 \pm 0.3) \times 10^{-12}\text{ cm}^{-2}\text{s}^{-1}$ for Terzan 5 (Abramowski et al. 2011) and $I(>800\text{ GeV}) < 6.7 \times 10^{-13}\text{ cm}^{-2}\text{s}^{-1}$ for 47 Tucanae (Aharonian et al. 2009). The expectation of the VHE flux for Terzan 5 seems to be larger by a factor of ~2 than the HESS observation.
This may indicate that $f_e$ should not be as high as $\sim 1$. However, we note that there are other uncertainties which also affect the prediction of the VHE fluxes, such as the magnetic field inside the clusters, the injection spectrum, and the diffusion of electrons (Bednarek & Sitarek 2007).

Another counterpart to the GeV $\gamma$-ray excess is obviously the radio MSPs. The Square Kilometre Array (SKA) will provide a complete census of pulsars in the Galaxy (Cordes et al. 2004; Smits et al. 2009) and complement the CTA observations.

**Note Added in Proof:** When this work was in its final stage, we became aware of a similar work by Petrović et al. (2015), which discussed ICS emission from MSPs.

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