Discovery of a Spatially Extended GeV Source in the Vicinity of the TeV Halo Candidate 2HWC J1912+099: a TeV Halo or Supernova Remnant?

Hai-Ming Zhang1,4, Shao-Qiang Xi1,4, Ruo-Yu Liu1,2, Yu-Liang Xin3, Siming Liu3, and Xiang-Yu Wang1,4

1 School of Astronomy and Space Science, Nanjing University, Nanjing 210023, People’s Republic of China; xywang@nju.edu.cn, ryliu@nju.edu.cn
2 Deutsches Elektronen Synchrotron (DESY), Platanenallee 6, D-15738 Zeuthen, Germany
3 Purple Mountain Observatory and Key Laboratory of Radio Astronomy, Chinese Academy of Sciences, Nanjing 210008, People’s Republic of China
4 Key Laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, Nanjing 210023, People’s Republic of China

Received 2019 September 29; revised 2019 November 20; accepted 2019 November 22; published 2020 January 20

Abstract
Observations by the High-Altitude Water Cherenkov Observatory (HAWC) and Milagro have detected spatially extended TeV sources surrounding middle-aged (t ~ 100–400 kyr) pulsars like Geminga and PSR B0656+14, which have been named “TeV halos,” representing very extended TeV pulsar wind nebulae (PWNe) powered by relatively old pulsars. A few more HAWC-detected sources have been suggested to be TeV halo candidates. In this paper, we search for possible GeV counterparts of three TeV halo candidates with Fermi Large Area Telescopes. We detect a new spatially extended GeV source in the vicinity of the TeV halo candidate 2HWC J1912+099, which is also detected by the High Energy Stereoscopic System (H.E.S.S.) (HESS J1912+101). We find that the size of the GeV source is significantly larger than that of the TeV emission measured by H.E.S.S., and a spatial template characteristic of a PWN can fit the GeV data. We suggest that the GeV source is an extended PWN powered by the central middle-aged pulsar PSR J1913+1011. This discovery favors the TeV halo scenario for the TeV source 2HWC J1912+099 (HESS J1912+101), although the possible shell-like morphology measured by H.E.S.S. challenges this interpretation. Alternatively, the TeV emission could be dominated by a supernova remnant via the hadronic process. Future multi-wavelength observations of the source and more precise measurements of the spatial profile of the TeV emission will be useful to distinguish between the two scenarios.

Unified Astronomy Thesaurus concepts: Pulsars (1306); Cosmic rays (329); High-energy cosmic radiation (731)

1. Introduction
Observations by Milagro (Abdo et al. 2009), along with recent observations by HAWC (Abeysekara et al. 2017a), have revealed extended TeV emissions (i.e., TeV halos) surrounding Geminga and PSR B0656+14. The angular sizes of the TeV halos are much larger than the X-ray pulsar wind nebulae (PWNe). The measurements of surface brightness profile of these TeV halos suggest inefficient diffusion of particles from the sources, giving rise to a debate on the pulsar interpretation of the cosmic-ray positron excess (Abeysekara et al. 2017b). Xi et al. (2019) argued that GeV observations provide more direct constraints on the positron density in the TeV nebulae in the energy range of 10–500 GeV and hence on the origin of the observed positron excess. Motivated by this, they searched for GeV emission from the two TeV halos with the Fermi Large Area Telescope (LAT). No convincing GeV counterparts are detected from these two TeV halos which suggests a relatively low density of GeV electrons/positrons in the TeV halos, thereby constraining their contribution to the positron excess (Xi et al. 2019). Considering the proper motion of the Geminga pulsar and one-zone diffusion spatial templates, which leads to a very large size for the source, Di Mauro et al. (2019) claimed the detection of GeV emission from the Geminga TeV halo. However, the large size could lead to serious contamination from the background, so the result is still uncertain.

A few more TeV halo candidates have been suggested by Linden et al. (2017), based on the HAWC source catalog (Abeysekara et al. 2017a). These include 2HWC J1912+099, 2HWC J1831-098, and 2HWC J2031+415 (Abeysekara et al. 2017a). Motivated by these observations, we attempt to search for possible GeV counterparts of these TeV halo candidates. 2HWC J1912+099 is spatially coincident with HESS 1912+101, which is found in the Galactic plan survey by H.E.S.S. HESS 1912+101 is suggested to be a possible supernova remnant (SNR) based on the shell-like morphology of the TeV emission (H.E.S.S. Collaboration et al. 2018). However, the suggested size of the TeV emission measured by HAWC is different from the H.E.S.S. source (Abeysekara et al. 2017a), which may be due to different fields of view (FOV) and sensitivities of the two telescopes.

The area of HESS J1912+101 was covered by the NRAO/Very Large Array Sky Survey at 1.4 GHz (Condon et al. 1998) and the new Multi-Array Galactic Plane Imaging Survey (Helfand et al. 2006), but no obvious counterpart to the TeV source was found (H.E.S.S. Collaboration et al. 2018).

Recently, Reich & Sun (2019) analyzed the Sino–German Urumqi λ6 cm survey and found a partial shell of possible excessive polarization at λ6 cm at the periphery of HESS J1912+101, but they could not separate the shell’s total intensity signal from the confusing intense diffuse emission from the inner Galactic plane. To be conservative, since the significance of polarization is low, we use their total flux density of 2.5 ± 1.0 Jy, which is inferred from the polarization flux, as an upper limit at λ6 cm (Reich & Sun 2019). Archival Chandra data from observations targeting PSR J1913+1011 (and only covering the central region of HESS J1912+101) were analyzed by Chang et al. (2008) to search for X-ray counterparts, but no convincing X-ray counterpart was detected. As no low-energy (radio and X-rays) counterparts have been found so far, the nature of this source is quite uncertain.
In Section 2, we perform an analysis on the Fermi-LAT data toward the region of 2HWC J1912+099 (HESS 1912+101). We focus on the spatial extension analysis of the GeV emission using different spatial templates. In Section 3, we consider a physically motivated template, i.e., the GeV emission is produced by diffusing electrons as in the TeV halos (hereafter named “diffusion” templates). In Section 4, we present the spatial analysis of the other two TeV halo candidates, 2HWC J1831-098 and 2HWC J2031+415. Finally, we give discussions in Section 5.

2. Fermi/LAT Data Analysis

The LAT on board the Fermi Gamma-ray Space Telescope has continuously monitored the sky since 2008 and scans the entire sky every 3 hr (Atwood et al. 2009). For this work we use the Pass 8 SOURCE data taken from 2008 August 4 to 2019 January 19 to study the extended gamma-ray emission around HESS J1912+101. We select the γ-ray events in the 10–500 GeV energy range, using standard data quality selection criteria “(DATA.Qual > 0) && (LAT.Config == 1)” Since we are only considering high-energy (>10 GeV) γ-ray events, for which the point-spread function is relatively good, the maximum zenith angle is set to be 105°. Data within a 14° × 14° radius of interest centered on the position of HESS J1912+101 are binned in 12 logarithmically spaced bins in energy and a spatial binning of 0.1° per pixel is used. We utilize the publicly available software fermitools (ver. 1.0.0). The P8R3_SOURCE_V2 set of instrument response functions is used.

For the background model, we include the diffuse Galactic interstellar emission (gll _iem _v07.fits) and isotropic emission (“iso _P8R3 _SOURCE _V2 _v1.txt”) templates released by the Fermi Science Support Center, as well as individual gamma-ray sources listed in the Fourth Catalog of Fermi-LAT Sources (4FGL; The Fermi-LAT collaboration 2019). Considering that the background point source 4FGL J1913.3+1019 is reported to be associated with a radio pulsar, PSR J1913+1011, which is only ~0°140 away (R.A. = 288°335, decl. = 10°19; Morris et al. 2002), we re-locate the position of 4FGL J1913.3+1019 to that of PSR J1913+1011 in the analysis.

In subsequent analysis, the normalization and spectral parameters of the discrete gamma-ray sources within 5° in the background model are left free. We also free the normalizations of the isotropic and Galactic components. Note that the typical cutoff energies of the sources shaped by the LogParabola function are smaller than 10 GeV, we thus free only the normalization of the LogParabola function in order to get a convergence of fitting.

We search for possible GeV emission around the region of HESS J1912+101. First, we perform a background-only fitting and obtain the test statistic (TS) map, as shown in Figure 1. The TS value is defined as $TS = 2(\ln L_1 - \ln L_0)$, where $L_0$ is the likelihood of background (null hypothesis) and $L_1$ is the likelihood of the hypothesis for adding a source. An obvious excess is located in the region of HESS J1912+101. Then, we create a series of spatial templates to test the extension of the excess emission. To define a source to be extended, $TS_{\text{ext}} \geq 16$ is required ($TS_{\text{ext}} = 16$ corresponds to a formal 4σ significance; Ackermann et al. 2017), where $TS_{\text{ext}} = 2(\ln L_{\text{ext}} - \ln L_{\text{ps}})$, with $L_{\text{ext}}$ and $L_{\text{ps}}$ being the likelihoods of hypothesis for adding an extended source and a point-like source, respectively (Lande et al. 2012).

2.1. Single Point-like Source Model

First, we consider a point-like source model. We add a point-like source at the position of the peak TS value into our background model, and optimize the localization using the gfindsrc tool. The derived best-fit location of the excess above 10 GeV is $(288°405, 10°361) \pm 0°028$. The significance of the excess γ-ray emission is $TS = 45.3$ (6.7σ). The spectrum and flux in this model are shown in Table 1.
To investigate whether the γ-ray excess is an extended source spatially, we first consider a uniform-disk template. We select the best-fit position of the point-like source as the center of the disk, and vary the disk radii from 0°.1 to 2°.0 in steps of 0°.1 to search for the best-fit radius. We also vary the radii in steps of 0°.05 around the best-fit radius found in the first step to get a more precise radius. The best-fit is found at a disk radius of $R_{\text{disk}} = 0°.85 \pm 0°.08$ with TS = 68.5 (8.3σ), as shown in Figure 2. Since we have $T_{\text{ext}} = 23.1$ relative to a single-point-source model, the GeV source is spatially extended. The radius of GeV emission is larger than that of the TeV emissions measured by HAWC and H.E.S.S., which are about 0°.7 and 0°.5, respectively (Abeysekara et al. 2017a; H.E.S.S. Collaboration et al. 2018).

### 2.4. 2D Gaussian Template

The other model for studying the source extension in standard *Fermi*-LAT analysis is the two-dimensional (2D) Gaussian model. We set the center of 2D Gaussian at the best-fit position of the point-source model, and vary $\sigma$ from 0°.1 to 1°.3 in steps of 0°.1 to search the best-fit $\sigma$. Also we consider a step of 0°.01 around the best-fit $\sigma$ found in the first step. We define the source size as the radius containing 68% of the intensity, $R_{68} = 1.51\sigma$, as suggested by Lande et al. (2012). The best-fit is found at $\sigma = 0°.42 \pm 0°.03$, corresponding to 68% containment radius $R_{68} = 0°.63 \pm 0°.05$, with TS = 76.7 (8.8σ), as shown in Figure 2. The significance of extension in the 2D Gaussian model is $T_{\text{ext}} = 31.4$ (5.6σ) relative to a single point-source model.

### 3. Diffusion Templates in the TeV Halo Scenario

The fact that the size of the GeV source is significantly larger than that of the TeV source is consistent with the scenario of the counterpart of a TeV halo (i.e., an extended GeV PWN), considering that GeV-emitting electrons have longer cooling time so they diffuse to a larger extent. Although the shell-like morphology measured by H.E.S.S. is not expected in the TeV halo scenario, we note that the morphology and size measured by HAWC are different, so it is still unclear whether the TeV halo scenario can be excluded. On the other hand, interpreting the GeV source as an extended PWN does not necessarily require the TeV source be dominated by the PWN. The TeV source can be interpreted as other sources, such as an SNR.

In the PWN scenario, the GeV emission is produced by diffusing electrons injected from the pulsar via inverse Compton scattering on the interstellar radiation. To study this possibility, we calculate the spatial template under the isotropic diffusion model. The details of the calculation on the gamma-ray emission and their spatial distribution can be found in Xi et al. (2019) and Liu et al. (2019). The magnetic field strength in the surrounding ISM is assumed to be $B = 5 \mu G$, and the interstellar radiation field (ISRF) consists of, in addition to cosmic microwave background (CMB), a 20 K far-infrared radiation with energy density of

![Figure 2.](image-url)
0.4 eV cm\(^{-3}\), a 1300 K near-infrared radiation with energy density of 0.6 eV cm\(^{-3}\), and a 6500 K optical radiation with energy density of 0.2 eV cm\(^{-3}\) following the ISRF model by Popescu et al. (2017). To model the injection history of electron/positron pairs from the pulsar, we assume an initial rotation period of 15 ms and a braking index of 3 for the pulsar, which then results in a pulsar age of \(t_{\text{age}} \approx 140\) kyr. A fraction of \(\eta_p\) of the spin-down luminosity of the pulsar is assumed to be converted into the energy of pairs that are injected in a power-law spectrum with a slope \(p\). We then estimate the required diffusion coefficient to be \(D \approx 10^{27} (E/1 \text{ TeV})^{1/3} \text{ cm}^2 \text{ s}^{-1}\) in order to explain the spatial extension of the GeV emission within the pulsar’s age, given the best-fit \(\sigma = 0.42\) in the 2D Gaussian template, which corresponds to 30 pc at a nominal distance of 4.5 kpc. This diffusion coefficient is about two orders of magnitude lower than the ISM value, consistent with the value found for the Geminga TeV halo (Abeysekara et al. 2017b). Since the position of the maximum TS is \(\sim 0^\circ.15\) from the pulsar in the excess map, we have taken into account the proper motion of the pulsar by assuming a plane-of-sky velocity \(v = 0^\circ.15/t_{\text{age}} \approx 3.85 \text{ mas yr}^{-1}\) or 83 km s\(^{-1}\).

Depending on whether the measured TeV emission has the same origin as the GeV emission, we obtain two templates with different spectral indices (denoted by \(p\)) for the injected electron/positron pairs \((dN_e/d\gamma \propto \gamma^{p})\), and the predicted flux is compared with data in Figures 3 and 4. We generate the diffusion templates using the mapcube file, which is a three-dimensional FITS map allowing arbitrary spectral variation as a function of sky position and cut at 2\(^\circ\). For \(p = 1.6\) and \(\eta_p = 0.06\), the measured TeV flux can be fitted simultaneously, with the TS value being 64.3 (8.0\(\sigma\)) for the GeV source. In the other template, a softer injection spectrum with \(p = 2.0\) is assumed, and the TS value is 67.5 (8.2\(\sigma\)) for the GeV source. As the significance (\(\sqrt{\text{TS}}\)) of the signal for these two diffusion templates is comparable to that of the Gaussian and disk templates, a possible physical explanation is that the GeV source is an extended PWN powered by PSR J1913+1011.

4. Discussions on the Origin of the GeV/TeV Source

In this section, we discuss the possible nature of the GeV and TeV emission. One scenario for the GeV and TeV emissions is that they both arise from a PWN, produced by diffusing electrons that upscatter the CMB and ambient photons. The advantage of this scenario is that it can naturally explain the fact that the size of the GeV emission is significantly larger than that of the TeV emission measured by H.E.S.S. As shown by Figure 5, the angular profile of TeV emission in the PWN scenario is steeper than that of the GeV emission due to stronger radiative cooling for TeV-emitting electrons, i.e., the intensity of TeV emission decreases more quickly with the distance to the center, which may explain the more compact size of the TeV emission. Indeed, some known PWNe, such as
HESS J1825-137, show a clear energy-dependent morphology, with smaller sizes at higher energies (H.E.S.S. Collaboration et al. 2019). Modeling of the spectral energy distribution (SED) with this scenario is shown in Figure 3. The hard electron index \( p = 1.6 \) is not unusual for PWNe. However, this scenario cannot explain the possible shell-like morphology of the TeV emission, as suggested by recent H.E.S.S. observations (H.E.S.S. Collaboration et al. 2018), since the intensity in the PWN scenario is expected to decrease smoothly with the distance to the center. Since the FOV of H.E.S.S. is relatively small, a more clear angular profile of the TeV emission would require observations by larger-FOV telescopes, such as HAWC and the Large High Altitude Air Shower Observatory.

If the shell-like morphology is true, the TeV source may originate from an SNR (Su et al. 2017; H.E.S.S. Collaboration et al. 2018). Given the relatively short radiative energy loss time of electrons producing TeV emission, it has been suggested that the shell-like TeV emission may be due to hadronic interactions between high-energy protons accelerated by the SNR and the surrounding high-density molecular gas (Su et al. 2017). The GeV source can still be interpreted as an extended PWN in this scenario, as long as the TeV counterpart of the extended GeV PWN is dim, being outshone by the TeV SNR emission. The SED modeling with these two components (i.e., PWN plus SNR) is shown in Figure 4. With a total energy of protons above 1 GeV of \( 3 \times 10^{48} (n/5 \text{ cm}^{-3})^{-1} \text{ erg} \), where \( n \) is the mean ambient density, the hadronic emission from the SNR contributes significantly to the observed TeV emission. The maximum energy of the SNR-accelerated protons needs to be \( E_m > 100 \text{ TeV} \) in this scenario. Such a high maximum energy is challenging for an old SNR with an age of 170 kyr. One possible solution is that these energetic protons were accelerated in the early stage of the SNR evolution and they are still trapped by molecular clouds, giving rise to the observed TeV emission (Zeng et al. 2019).

5. 2HWC J1831-098 and 2HWC J2031+415

Two other TeV halo candidates (2HWC J1831-098 and 2HWC J2031+415) have been reported by Linden et al. (2017). 2HWC J1831-098 is an extended source (0.7 disk) reported to be associated with the TeV source HESS J1831-089, a candidate PWN powered by the pulsar PSR J1831-0952 (Linden et al. 2017). 2HWC J2031+415 (0.7 disk) is associated with the TeV source J2031+4130 detected by HEGRA in 2002, a PWN first reported as an unidentified source in TeV band (Aharonian et al. 2002). We apply the same Fermi-LAT analysis to these sources. We found no significant excess in GeV emission by testing different spatial templates for 2HWC J1831-098 in the energy band 10–500 GeV, as shown in Figure 6. An upper limit flux of \( 3.09 \times 10^{-12} \text{ erg cm}^{-2} \text{s}^{-1} \) (95% confidence level) is obtained, assuming a spectral index of 2.0 and a uniform-disk template of radius 0.7° (centered at 2HWC J1831-098). We compare this GeV flux limit measured by Fermi-LAT with the TeV flux of 2HWC J1831-098 and find that the upper limit is significantly lower than the TeV flux (\( 7.60 \times 10^{-12} \text{ erg cm}^{-2} \text{s}^{-1} \)). This may imply that a hard electron index is needed in the PWN scenario for the GeV and TeV emissions, which is quite similar to the Geminga TeV halo (Xu et al. 2019).

The source 2HWC J2031+415 is located within the region of the GeV-bright Cygnus Cocoon (distance of \( 0.6^\circ \)). The diffuse emission in this region was fitted by a 2D Gaussian model with \( \sigma = 3.0^\circ \) by the Fermi collaboration (The Fermi-LAT collaboration 2019). As seen in the right panel of Figure 5, after subtracting the emission of the Cygnus Cocoon, no significant excess is found in the residual map. Therefore, it is hard to identify possible GeV emission from 2HWC J2031+415 in the region of the bright Cygnus Cocoon. For this reason, we do not analyze this source further.

6. Conclusions

Using \( \sim 10.4 \text{ yr} \) of Fermi-LAT data, we discovered a new extended GeV source in the vicinity of the TeV source 2HWC J1912+099, which is also detected by H.E.S.S. (HESS J1912+101). The best-fit extension of the GeV \( \gamma \)-ray emission is \( 0.85 \pm 0.08 \) using the uniform-disk template, significantly larger than the size of the TeV emission measured by H.E.S.S. (\( \sim 0.5^\circ \)). Considering also that there is a middle-aged radio pulsar PSR J1913+1011 at the center of the GeV/TeV emission, we studied the possibility that the GeV/TeV source is an extended PWN, i.e., a TeV halo. Then we test various diffusion templates, which assumes that the GeV emission is produced by diffusing electrons, and find that the diffusion spatial templates give an almost equally good fit to the data as the uniform-disk spatial template and Gaussian spatial template. Thus, the GeV source...
can be interpreted as an extended PWN. However, the possible shell-like morphology of the TeV emission, if true, is inconsistent with this scenario.

Alternatively, the shell-like TeV morphology may be attributed to emission from an SNR. In this scenario, the TeV emission is likely produced by ions interacting with the surrounding high-density molecular gas (Su et al. 2017), given the very short radiative loss time for TeV-emitting electrons. By studying a sample of 34 $\gamma$-ray SNRs, Zeng et al. (2019) found that the acceleration of TeV particles usually stops before the end of the Sedov phase when the remnant is $\lesssim 10$ kyr, which is much shorter than the age (170 kyr) of the system. One possible solution to this dilemma is that these energetic protons were accelerated in the early stage of the SNR evolution, and they are still trapped by molecular clouds, producing the observed TeV emission. The GeV source can still be interpreted as an extended PWN with its TeV emission outshone by the SNR. This is possible if the electron spectrum of the PWN is soft. A precise measurement of the angular profile of the TeV emission in the future will be useful to diagnose the electron diffusion in the TeV halo scenario. Meanwhile, future deeper multi-wavelength observations to search for the low-energy counterparts of a potential SNR will be useful to test the SNR scenario.

We thank the referee for the constructive report and Hui Zhu for useful discussions. The work is supported by the National Key R & D program of China under the grant 2018YFA0404203 and the NSFC grants 11625312 and 11851304.

ORCID iDs
Ruo-Yu Liu @ https://orcid.org/0000-0003-1576-0961
Siming Liu @ https://orcid.org/0000-0003-1039-9521
Xiang-Yu Wang @ https://orcid.org/0000-0002-5881-335X

References
Abdo, A. A., Allen, B. T., Aune, T., et al. 2009, ApJL, 700, L127
Abeysekara, A. U., Albert, A., Alfaro, R., et al. 2017a, ApJ, 843, 40
Abeysekara, A. U., Albert, A., Alfaro, R., et al. 2017b, ApJ, 838, 911
Ackermann, M., Ajello, M., Baldini, L., et al. 2017, ApJ, 843, 139
Aharonian, F., Akhperjanian, A., Beilicke, M., et al. 2002, A&A, 393, L37
Atwood, W. B., Abdo, A. A., Ackermann, M., et al. 2009, ApJ, 697, 1071
Chang, C., Konopelko, A., & Cui, W. 2008, ApJ, 682, 1177
Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, AJ, 115, 1693
Di Mauro, M., Manconi, S., & Donato, F. 2019, arXiv:1903.05647
Helfand, D. J., Becker, R. H., White, R. L., Fallon, A., & Tuttle, S. 2006, AJ, 131, 2525
H.E.S.S. Collaboration, Abdalla, H., Abramowski, A., et al. 2018, A&A, 612, A8
H.E.S.S. Collaboration, Abdalla, H., Abramowski, A., et al. 2019, A&A, 621, A116
Lande, J., Ackermann, M., Allafort, A., et al. 2012, ApJ, 756, 5
Linden, T., Auchettl, K., Bramante, J., et al. 2017, PhRvD, 96, 103016
Liu, R.-Y., Ge, C., Sun, X.-N., et al. 2019, ApJ, 875, 149
Morris, D. J., Hobbs, G., Lyne, A. G., et al. 2002, MNRAS, 335, 275
Popescu, C. C., Yang, R., Tufts, R. J., et al. 2017, MNRAS, 470, 2539
Reich, W., & Sun, X.-H. 2019, ARA&A, 19, 045
Su, Y., Zhou, X., Yang, J., et al. 2017, ApJ, 845, 48

The Fermi-LAT collaboration 2019, arXiv:1905.10771
Xi, S.-Q., Liu, R.-Y., Huang, Z.-Q., Fang, K., & Wang, X.-Y. 2019, ApJ, 878, 104
Zeng, H. D., Xin, Y. L., & Liu, S. M. 2019, ApJ, 874, 50