DETECTION OF GEV $\gamma$-RAY EMISSION FROM SUPERNova REMnANT SNR G15.9+0.2 WITH FERMI-LAT

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ABSTRACT

We first report GeV $\gamma$-ray emission from supernova remnant (SNR) G15.9+0.2 in this work. The results show that its power-law spectral index is $2.94 \pm 0.25$ with a $6.47 \sigma$ significance level, and the $\gamma$-ray emission can be characterized by a two-dimensional (2D) Gaussian spatial distribution, which has a better improvement than the case of a point source. Moreover, we find that its likely counterparts from the radio, X-ray, and TeV energy bands are well coincident with its spatial location. We suggest that the new $\gamma$-ray emission may originate from SNR G15.9+0.2. Analyzing the variability from 12.4 years of the light curve (LC), we identify that this LC exists weak variability with a $2.69 \sigma$ variability significance level. We investigated the 2D Gaussian extended region and did not identify certified active galactic nuclei from the region of this SNR; thus, we suggest that the new $\gamma$-ray emission may originate from SNR G15.9+0.2. On this basis, we discussed the probable origins of its $\gamma$-ray radiation from leptonic and hadronic scenarios, respectively.

Keywords: supernova remnants - individual: (SNR G15.9+0.2) - radiation mechanisms: non-thermal

1. INTRODUCTION

Supernova remnant (SNR) is considered to be an efficient cosmic-ray factory. After the explosion of SNR, it is considered that the 10% kinetic energy of SNR transferred to CRs, and the maximum energy of cosmic-ray particles can be accelerated to approximately $10^{15}$ eV through the diffusive shock acceleration mechanism (Bell 1978; Blandford & Eichler 1987; Drury et al. 1994; Morlino & Caprioli 2012). Their multiband spectra exhibit a typical bimodal structure through leptonic or/and hadronic processes (e.g., Zeng et al. 2019, 2021). For the radio-to-X-ray band, it is generally recognized that synchrotron radiation dominates (Allen et al. 1997, 1999; Uchiyama et al. 2007). For the GeV-to-TeV energy band, inverse Compton scattering and bremsstrahlung of relativistic electrons are generally considered to be important mechanisms (Vink 2012). In addition, decay of neutral pions produced in the inelastic hadronic interaction becomes more and more important to explain the GeV and TeV emissions of SNRs (e.g., Xin et al. 2017, 2019; Yang et al. 2021; Xiang & Jiang 2021). Detection of GeV $\gamma$-ray emission of SNR is very important for evaluating SNR’s contribution to cosmic-ray flux in Milky Way (Acero et al. 2016), and it can also help us explore the acceleration mechanism of cosmic-ray particles and limit the energy distribution of accelerated particles, which provides further understanding of the evolution process of cosmic-ray particles in SNRs (Zhang & Fang 2007; Finke & Dermer 2012; Tang et al. 2013). Thus far, only 24 SNRs have been firmly certified in the Fermi Large Telescope Fourth Source Catalog (4FGL; Abdollahi et al. 2020). Therefore, more GeV SNRs are required to recognize the nature of particle acceleration within SNRs.

Caswell et al. (1982) found a clear shell structure from SNR G15.9+0.2 at 1415 MHz with about 58$''$ resolution using the Fleurs synthesis radio telescope. Based on the observations at 327.5 MHz and 1425 MHz from the NRAO VLA sky survey (NVSS), Dubner et al. (1996) found that the eastern border of SNR G15.9+0.2 had a bright shell feature; the northwest edge had two fainter knots; the north of the shell appeared an extension region of the radio emission with a 3$\sigma$ noise level at 1425 MHz. Through XMM-Newton observations, Maggi & Acero (2017) found the evidence of spatial variations by measuring the Fe K line features. They believed that SNR G15.9+0.2 with the lowest Fe K centroid energy is the core-collapse SNR. Moreover, they identified ejecta emission from this SNR by observing the Fe K line features. They identified that the progenitors of SNR G15.9+0.2 originated from a massive star, according to the observation the abundance ratios of Ca, Ar, S, Si, and Mg.

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For the GeV band data, Acero et al. (2016) did not find significant GeV $\gamma$-ray emission of the SNR in the 1-100 GeV energy band using the Fermi Large Area Telescope (Fermi-LAT), and they provided its upper limits with the 95% and 99% confidence level for the power-law spectral indices of 2.0 and 2.5, respectively. For the TeV energy band, Abeysekara et al. (2017) found that the TeV source 2HWC J1819-150 is closer to SNR G15.9+0.2 with a position separation of 0°.1. In addition, the differential flux at 7 TeV is $59.0\pm7.9\times10^{-15}$ TeV$^{-1}$ cm$^{-2}$ s$^{-1}$ with a spectral index of $-2.88\pm0.10$.

In this study, for the improvement and accumulation from the Fermi-LAT Pass 8 data and the update of $\gamma$-ray background models from galactic diffuse emission and the isotropic extragalactic emission (Abdollahi et al. 2020), the GeV $\gamma$-ray emission of SNR G15.9+0.2 was reanalyzed using approximately 12.4 years of the Pass 8 data. In the preliminary analysis, a likely GeV $\gamma$-ray emission from the region of SNR G15.9+0.2 was found, which strongly inspired us to explore the characteristics and origin of this GeV $\gamma$-ray emission in this study. Subsequent works include the introduction of data reduction in Section 2, the presentation of the analysis results in Section 3, and the discussion and conclusion about the likely origins of the GeV radiation in Section 4.

2. DATA REDUCTION

Using FermiTools version v11r5p3$^1$, we analyzed the GeV $\gamma$-ray emission from the region of SNR G15.9+0.2 by selecting the instrumental response function (IRF) “P8R3\_SOURCE\_V3” and the Pass 8 “Source” event class (evtype = 3 and evclass = 128). The observation period was selected to be from August 4, 2008, to December 29, 2020 (mission elapsed time (MET) 239557427-630970757). The energy range was selected to be 1-500 GeV to reduce contamination from the galactic diffuse emission for a large point spread function in the low-energy band. Photon events with the maximum zenith angles of 90° were selected to suppress the pollution from the Earth Limb. A $20^\circ \times 20^\circ$ region of interest (ROI), centered at the position from SIMBAD (R.A., decl. = 274°.83, -15°.03) $^2$, was selected for this analysis. We selected the script make4FGLxml.py$^3$ to generate a source model file, and sources from the 4FGL within the ROI of 30° were included in the model file. Then, we included a point source with a power-law spectrum at the SIMBAD location of SNR G15.9+0.2 to the model file. The binned likelihood tutorial$^4$ was followed in the analysis. Furthermore, spectral indexes and normalizations from sources within the 5° range of the ROI were set as free in the model file. The normalizations from the isotropic extragalactic emission (iso\_P8R3\_SOURCE\_V3\_v1.txt) and the galactic diffuse emission (gll\_iem\_v07.fits)$^5$ were also set as free.

3. SOURCE DETECTION

Running the command gttsmap, the test statistic (TS) map, which is centered at the SIMBAD location of SNR G15.9+0.2 in the 1-500 GeV energy band, was first calculated in this analysis. In the left panel of Figure 1, significant $\gamma$-ray radiation with a TS value = 30.20 was found in the region of SNR G15.9+0.2. Here, the TS value, defined as $TS = 2\log(L_1/L_0)$ from (Mattox et al. 1996), is calculated to quantify a significant source, and $L_1$ and $L_0$ represent maximum-likelihood values; $L_1$ contains target source; $L_0$ does not contain. In addition, we identified three significant $\gamma$-ray excesses from the locations of P1, P2, and P3. Then, we chose to add these three point sources, with power-law spectra in the local maxima of the TS map, to their locations$^6$ to subtract the three significant residual emissions within the $2^\circ.6 \times 2^\circ.6$ TS map for all subsequent analyses. As shown in the right panel of Figure 1, the $\gamma$-ray radiation was still significant with the TS value of 29.61 in the region of SNR G15.9+0.2.

To further confirm that the region of SNR G15.9+0.2 does not have other significant $\gamma$-ray residual radiations within the $2^\circ.6 \times 2^\circ.6$ TS map, we also deducted the emission from the region of SNR G15.9+0.2. Using gtfindsrc, we obtained the best-fit position of SNR G15.9+0.2 to be (R.A., decl. = 274°.74, -14°.92) with a 68% (95%) error circle of 0°.10 (0°.16) by assuming a point source with a power-law spectrum at its SIMBAD location. As shown in Figure 2, we found its contours of the 1.4 GHz radio and X-ray energy bands are all within the 68% and 95% error circles of the best position of SNR G15.9+0.2. Moreover, the region with a 1σ statistical uncertainty from the location of the TeV source 2HWC J1819-150 (R.A., decl. = 274°.83, -15°.06; from Abeysekara et al. (2017) well overlaps with all the regions from three different energy bands. This indicates that these four sources from the radio to TeV bands are likely to be counterparts of SNR G15.9+0.2.

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1. http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html
2. http://simbad.u-strasbg.fr/simbad/
3. https://fermi.gsfc.nasa.gov/ssc/data/analysis/user/
4. https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/binned_likelihood_tutorial.html
5. http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/
6. The location of P1: (R.A., decl.=275°.63, -14°.11); that of P2: (R.A., decl.=273°.49, -13°.99); that of P3: (R.A., decl.=274°.39, -16°.21).
Figure 1. These TS maps of 2°.6 × 2°.6, which were smoothed with a Gaussian function with a kernel radius of 0°.3, in the 1-500 GeV energy band with a 0°.04 pixel size centered at the SIMBAD position of SNR G15.9+0.2 marked as a white cross. The 68% and 95% error circles of the best-fit position of this SNR are marked by using solid and dashed cyan circles in these TS maps, respectively. Left panel: TS map including all the 4FGL sources and the residual radiations in the region. Right panel: TS map after deducting three γ-ray excesses including P1-P3.

Figure 2. TS map of the region of 1°.6 × 1°.6 is smoothed with a Gaussian kernel of 0°.3 with a 0°.04 pixel size in the 1-500 GeV energy band centered at the SIMBAD position of SNR G15.9+0.2. Two solid and dashed cyan circles were introduced in Figure 1. The green contours are from 1.4 GHz observations of NVSS (Caswell et al. 1982), and the blue contours are from X-ray observations of XMM-Newton (Maggi & Acero 2017). A black cross represents the position (RA=274°.83, decl.=-15°.06) of 2HWC J1819-150, and its 1σ statistical uncertainty of this position is 0°.16, which is represented by a solid black circle (Abeysekara et al. 2017). The green circle indicates the extent of the GeV emission (2D Gaussian template) in this work.
Table 1. Spatial Distribution Analysis for SNR G15.9+0.2 with Different Spatial Models in The 1-500 GeV Energy Band

| Spatial Model     | Radius (σ) degree | Spectral Index | Photon Flux 10^{-9} ph cm^{-2} s^{-1} | TS Value | TS_{ext} | Degrees of Freedom |
|------------------|-------------------|----------------|---------------------------------------|----------|----------|-------------------|
| Point source     | -                 | 2.94±0.51      | 0.39±0.10                             | 29.61    | -        | 4                 |
| 2D Gaussian      | 0°.45             | 2.94±0.25      | 4.09±0.57                             | 55.67    | 26.06    | 5                 |
| uniform disk     | 0°.75             | 2.96±0.23      | 3.62±0.53                             | 50.93    | 21.32    | 5                 |

Figure 3. The SED of SNR G15.9+0.2 from the 1 GeV to 500 GeV energy band. Blue points indicate the result of the Fermi-LAT observation with the 1σ statistical uncertainties. The black solid line represents the result of the global fit with a power-law spectral model, and the two red dashed lines represent the 1σ statistical uncertainties of the global fit. The gray shaded areas represent the TS value of each energy bin. For the energy bins with TS values <4, the upper limits with a 95% confidence level are given.

Using the uniform disk and two-dimensional (2D) Gaussian templates, we tested the different values of the radius and σ, which range from 0°.1 to 1°.5 with an increment of 0°.05, to obtain the probable γ-ray spatial distribution of the new source. Then, we calculated the value of the TS_{ext}, using the formula of $2\log(L_{ext}/L_{ps})$ from Lande et al. (2012), where $L_{ps}$ and $L_{ext}$ represent the maximum log-likelihood values for the point source template and extended templates, respectively. We found that the 2D Gaussian template has a significant improvement with the highest value of TS_{ext} and a σ of 0°.45 in the analysis. Therefore, we adopted the 2D Gaussian spatial template with a σ of 0°.45 as the best spatial template to analyze the new γ-ray source in all subsequent analyses. The best-fit results with the highest TS values from the different templates were presented in Table 1.

3.1. Spectral Analysis

In this analysis, we generated the spectral energy distribution (SED) in the 1-500 GeV energy band using a power-law spectrum model with the formula, $dN/dE = N_0E^{-\Gamma}$, and the 2D Gaussian template for the new γ-ray source. The result of the global fit is $\Gamma = 2.94\pm0.25$; its photon flux is $(4.09\pm0.57) \times 10^{-9} \text{ph cm}^{-2} \text{s}^{-1}$. The SED was divided into 10 equal logarithmic bins. Each energy bin was fitted using the binned likelihood analysis method. For the energy bins with the TS value < 4, we calculated their upper limits with a 95% confidence level. Considering the subsequent energy bins with large statistical errors and the TS values < 4, here we selected to provide two upper limits for the SED, as shown in Figure 3.

3.2. Variability Analysis

To check the variability of the photon flux over 12.41 years for the new γ-ray source, we generated a light curve (LC) with 20 time bins in the 1-500 GeV energy band, as can be seen from Figure 4. Calculating the variability index
Figure 4. LC of SNR G15.9+0.2 with 20 time bins in the 1-500 GeV band. For the time bins with TS values < 4, the upper limits with a 95% confidence level are given. The gray shaded areas show the TS value of each time bin. The black solid line and the two black dashed lines are used to show the average photon flux from the maximum likelihood fit and its 1σ statistical uncertainties, respectively.

Table 1. Parameters of the best-fit 2D Gaussian spatial distributions and their statistical uncertainties.

| Parameter | Value | Uncertainty |
|-----------|-------|-------------|
| Mean X   | 500   | ±5          |
| Mean Y   | 600   | ±6          |
| σ X      | 20    | ±2          |
| σ Y      | 30    | ±3          |

TS$_{var}$ defined by Nolan et al. (2012), we acquired TS$_{var} = 37.39$ with a 2.69σ variability significance level$^7$. The result implies that the new γ-ray source exhibits a hint of weak variation$^8$.

4. DISCUSSION

By analyzing the above TS maps of SNR G15.9+0.2, we found that the region of SNR G15.9+0.2 has the significant GeV γ-ray radiation with a 2D Gaussian spatial distribution and a significance level of 6.47σ. Its photon flux is $(4.09\pm0.57) \times 10^{-9}$ ph cm$^{-2}$ s$^{-1}$ with Γ= 2.94±0.25. We observed that almost all the radio and X-ray contours from SNR G15.9+0.2 are all within the 2σ error circle of the best-fit location. In addition, the 1σ error circle also contains some contours from the radio and X-ray energy bands. These results suggest that the position of the new γ-ray source well coincides with SNR G15.9+0.2.

Next, we analyzed the variability of approximately 12.4 years of the LC and found that the LC exits a weak variability with a significance level of 2.69σ. Thus far, the variability from LCs of SNRs in the Milky Way likely exists, such as iPTF14hls (Yuan et al. 2018), Supernova 2004dj (Xi et al. 2020), the Crab Nebula (Arakawa et al. 2020). In addition, we investigated the 4FGL and found three certified SNRs with TS$_{var} > 18.48^9$, including W 51C, W 44, and IC 443, which implies the variability from the LC of SNR G15.9+0.2 is likely. We considered that the most significant GeV radiations of the region are concentrated in the 2D Gaussian region with 0°.45 radius, as displayed in Figure 2, and the LC of the region has weak variability. Then, we used SIMBAD$^{10}$ and Aladin$^{11}$ to investigate whether the 2D Gaussian extended region has certified active galactic nuclei (AGN). However, we did not find likely one; therefore, we suggest that the new GeV γ-ray emission is more likely to be from SNR G15.9+0.2.

We considered leptonic and hadronic scenarios to explain the GeV SED of SNR G15.9+0.2 from this work using a one-zone model from NAIMA (Zabalza 2015, and references therein). Here we assumed leptonic and hadronic particle distributions satisfy the following two particle distributions:

(1) A power law model (PL):

$$N(E) = N_0 \left( \frac{E}{E_0} \right)^{-\alpha},$$

$^7$ Here, the variability significance level is calculated by the SciPy package (Virtanen et al. 2020).

$^8$ TS$_{var} \geq 36.19$ was used to identify variable sources at a 99% confidence level for the LC of 20 time bins (Xiang & Jiang 2021).

$^9$ The value of TS$_{var} > 18.48$ over 12 intervals indicates that the source more than 99% chance is a variable source. Please refer https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermilpsc.html

$^{10}$ simbad.u-strasbg.fr/simbad/

$^{11}$ https://aladin.u-strasbg.fr/aladin.gml
(2) A power law with an exponential cutoff model (ECPL):

\[ N(E) = N_0 \left( \frac{E}{E_0} \right)^{-\alpha} \exp \left( -\frac{E}{E_{\text{cutoff}}} \right), \]

where \( E_0 \) is set to 10 GeV, \( N_0 \) represents the amplitude, \( E \) is the particle energy, \( \alpha \) is the spectral index, \( E_{\text{cutoff}} \) represents the break energy (Aradonian et al. 2006; Ambrogi et al. 2019; Xin et al. 2019; Xiang & Jiang 2021). In the fit, we used the Bayesian information criterion (BIC) to determine the goodness of fit of the two models (Schwarz 1978; Ambrogi et al. 2019). The related formula of BIC is $\log(n)k - 2\log(L)$, where $n$ represents the number of the observed data, $k$ represents the number of parameters of the model, and $L$ is the maximum likelihood value. We assumed that the radiation fields of the leptonic and hadronic models come from the extended region of the SNR.

For the leptonic scenario, the presence of very-high-energy (VHE) electrons are confirmed in SNRs (e.g., Tanimori et al. 1998), and the GeV and TeV emissions of SNRs are also observed (e.g., Ackermann et al. 2017; Abdalla et al. 2018a). Subsequently, the inverse Compton scattering from leptons was widely used to explain the SEDs of high-energy bands from SNRs (e.g., Tang et al. 2013; Condon et al. 2017; Zeng et al. 2017, 2019, 2021). Therefore, the leptonic model, as a frequently-used model, is considered in the analysis. Additionally, the detection of the characteristic pion-decay signature in IC 443 and W44 confirms that cosmic-ray protons can be accelerated in SNRs (Ackermann et al. 2013). The proportion of proton composition of the observed CR spectrum on Earth is 99%, suggesting that the hadronic contribution for the γ-ray emission from SNRs cannot be ignored (Liu et al. 2015). Recent studies have shown that the multi-band SED of certain SNRs can be better explained when considering the contribution of hadrons than a pure leptonic scenario. E.g., Puppis A (Xin et al. 2017), SNR G106.3+2.7 (Xin et al. 2019; Yang et al. 2021), Kepler’s SNR (Xiang & Jiang 2021). Consequently, we also considered the hadronic origin here.

The interaction between high-energy particles of SNR and the surrounding molecular cloud can serve as the important evidence for the hadronic origin (Wootten 1977; Denoyer 1979; Tatamatsu et al. 1990; Green et al. 1997; Reach & Rho 1999; Zhou et al. 2009; Kilpatrick et al. 2014). Here, we firstly investigated OH maser emission at 1720 MHz around SNR G15.9+0.2 from Green et al. (1997). However, we did not find the significant OH maser emission around SNR G15.9+0.2; thus, there is no convincing evidence to verify the interactions of SNR G15.9+0.2 with “OH” around SNR G15.9+0.2 from Green et al. (1997). However, we did not find the significant OH maser emission around SNR G15.9+0.2; thus, there is no convincing evidence to verify the interactions of SNR G15.9+0.2 with “OH” around SNR G15.9+0.2 from Green et al. (1997). Moreover, we found that BIC values of PL and ECPL are close, with the values of approximately 3 and 5, respectively. Therefore, the goodness of fit of PL and ECPL cannot be distinguished thus far. The actual particle distribution of the SNR needs more high-energy observation data to infer in the future (e.g., continuous Fermi-LAT observation above 7 GeV). Furthermore, we found that both PL and ECPL models have soft indexes for leptonic and hadronic scenarios. Since the timescale of particle acceleration in SNR is approximately hundreds to thousands of years Yuan et al. (2018), considering the current age of the SNR is approximately 1000-3000 years (Reynolds et al. 2006), this may prevent the particles in the SNR from being accelerated to a very high energy level, resulting in a rapid truncation above 1 GeV and presenting a soft spectral feature.

4.1. Summary

1. By analyzing approximately 12 years of Fermi-LAT Pass 8 data in the 1-500 GeV energy band, a new GeV source with 6.47σ is found from the region of SNR G15.9+0.2; its photon flux is $(4.09\pm0.57) \times 10^{-9} \text{ph cm}^{-2} \text{s}^{-1}$ with a
Figure 5. The $0.5^\circ \times 0.5^\circ$ velocity-integrated brightness temperature map, smoothed with a Gaussian kernel of $0.3^\circ$, from the CO Milky Way Survey (Dempsey et al. 2013). The color bar represents CO intensity with the units of K km s$^{-1}$. The 68% and 95% error circles of the best-fit position of this SNR are marked by using solid and dashed white circles in these TS maps, respectively. The green contours are from the observation of NVSS. The cyan contours are from the observation of XMM-Newton.

Figure 6. For the above two panels, the blue and red solid lines represent the best-fit results of PL and ECPL, respectively. Two upper limits are included in the fitting process. Left panel: the leptonic scenario that is dominated by the inverse Compton scattering. Right panel: the hadronic scenario that is dominated by the decay of neutral pions from the process of proton-proton interactions.

1. Its soft spectral index is $2.94 \pm 0.25$.

2. Its spatial distribution can be described by a 2D Gaussian spatial model with $\sigma = 0.45^\circ$.

3. The GeV spatial position of SNR G15.9+0.2 is in good agreement with those of the radio, X-ray, and TeV bands. This result suggests that the new GeV source is likely to be a counterpart of SNR G15.9+0.2.
4. Its LC presents a weak variability, which is likely for the currently observed SNRs in Milky Way.

5. Its SED can be explained by considering the leptonic and hadronic scenarios with PL and ECPL particle distribution models. For the hadronic origin, past observations show that there are dense CO molecular clouds around it, but such proton-proton interactions need to be further demonstrated in the future.

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REFERENCES

Abeysekara, A. U. et al. 2017, ApJ, 843, 40
Abdalla, H. et al. 2018a, A&A, 612, A1
Abdollahi, S. et al. 2020, ApJS, 247, 33
Acero, F. et al. 2016b, ApJS, 224, 8
Ackermann, M. et al. 2013, Sci, 339, 139
Acheron, F. et al. 2006, A&A, 449, 223
Allen, G. E. et al. 1997, ApJ, 487, L97
Allen, G.E., Gotthelf, E.V., Petre 1999, in International Cosmic Ray Conference, 3, 480
Ambrogi, L., Zanin, R., Casanova, S., De Oña Wilhelmi, E., Peron, G., Aharonian, F. 2019, A&A, 623, A86
Arakawa M., Hayashida M., Khangulyan D., Uchiyama Y., 2020, ApJ, 897, 33
Bell, A. R. 1978, MNras, 182, 147
Blandford, R., & Eichler, D., 1987, PhR, 154, 1
Caswell, J. L., Haynes, R. F., Milne, D. K., Wellington, K. J. 1982, MNras, 200, 1143
Condon, B., Lemoine-Goumard, M., Acero, F., Katagiri, H. 2017, ApJ, 851, 100
Dame, T., Hartmann, D., Thaddeus, P. 2001, ApJ, 547, 792
Dempsey, J. T., Thomas, H. S., Currie, M. J. 2013, ApJS, 209, 8
Denoyer, L. K. 1979a, ApJL, 232, L165
Drury, L. O., Aharonian, F. A., Völk, H. J. 1994, A&A, 287, 959
Dubner, G. M., Giacani, E. B., Goss, W. M., Moffett, D. A., & Holdaway, M. 1996, AJ, 111, 1304
Finke, J.D., & Dermer, C. D. 2012, ApJ, 751, 65
Green, A. J., Frail, D. A., Goss, W. M., Otrupcek, R. 1997, AJ, 114, 2058
H.E.S.S. Collaboration 2018, A&A, 612, A3
Kafexhiu, E., Aharonian, F., Taylor, A. M., Vila, G. S. 2014, Phys. Rev., D90, 123014
Kilpatrick, C. D., Bieging, J. H., Rieke, G. H. 2014, ApJ, 796, 144
Lande, J. et al. 2012, ApJ, 756, 5
Liu, B. et al. 2015, ApJ, 809,102
Maggi, P., & Acero, F. 2017, A&A, 597, A65
Mattox, J. R. et al. 1996, ApJ, 461, 396
Morlino, G., & Caprioli, D. 2012, AIPC, 1505, 241
Nolan, P. L. et al. 2012, ApJS, 199, 31
Reach, W. T., & Rho, J. 1999, ApJ, 511, 836
Reynolds, S. P. et al. 2006, ApJ, 652, L45
Schwarz, G. 1978, Ann. Stat., 6, 461
Tang, Y.Y., Dai, Z.C., Zhang, L. 2013, RAA, 13, 537
Tanimori, T. et al. 1998, APJ, 497, L25
Tatematsu, K., Fukui, Y., Iwata, T., Seward, F. D., Nakano, M. 1990, ApJ, 351, 157
Tian, W. W. et al. 2019, PASP, 131, 114301
Uchiyama, Y., Aharonian, F. A., Tanaka, T., Takahashi, T., Maeda, Y. 2007, Nature, 449, 576
Virtanen, P. et al. 2020, Nature Methods, 17, 261
Vink, J. 2012, A&ARv, 20, 49
Wootten, H. A. 1977, ApJ, 216, 440
Xiang, Y.C., & Jiang, Z.J. 2021, APJ, 908, 22
Xi S.Q. et al., 2020, APJ, 901, 158
Yuan Q. et al., 2018, ApJL, 854, L18
Zeng, H. et al. 2017, ApJ, 834, 114
Zeng, H., Xin, Y., Liu, S. 2019, ApJ, 874, 50
Zeng, H.D., Xin, Y.L., Zhang, S.N., Liu, S.M. 2021, ApJ, 910, 78
Zeng, H.D., Xin, Y.L., Zhang, S.N., Liu, S.M. 2021, ApJ, 910, 78

Table 2. The Best-fit Parameters of Leptonic and Hadronic Models

| Model Name | Particle Distribution | $N_0$ | $\alpha$ | $E_{\text{cutoff}}$ | $-\log(L)$ | BIC | $\chi^2/N_{\text{dof}}$ |
|------------|----------------------|-------|--------|----------------|-------------|-----|-----------------|
| Leptonic model | PL | $4.81^{+1.08}_{-1.25} \times 10^{45}$ | $4.8^{+0.07}_{-0.09}$ | — | -0.11 | 3.44 | $0.11^{+2}_{-2}$ = 0.07 |
| | ECPL | $2.44^{+0.55}_{-0.66} \times 10^{44}$ | $2.94^{+0.20}_{-0.23}$ | 243.46$^{+89.64}_{-68.42}$ | -0.03 | 4.89 | $0.03^{+0}_{-1} = 0.03$ |
| Hadronic model | PL | $5.74^{+0.52}_{-0.60} \times 10^{42}$ | $2.99^{+0.22}_{-0.20}$ | — | -0.13 | 3.48 | $0.13^{+2}_{-4} = 0.09$ |
| | ECPL | $6.17^{+0.93}_{-1.00} \times 10^{42}$ | $2.85^{+0.44}_{-0.40}$ | 201.81$^{+60.81}_{-68.14}$ | -0.10 | 5.03 | $0.10^{+2}_{-4} = 0.10$ |
Zhang, L., & Fang, J. 2007, ApJ, 666, 247
Zhou, X., Chen, Y., Su, Y., Yang, J. 2009, ApJ, 691, 516