Fermi-LAT Detection of GeV $\gamma$-Ray Emission from the Highly Asymmetric Shell Supernova Remnant SNR G317.3-0.2

Yunchuan Xiang1, Zejun Jiang1,3, and Yunyong Tang2

1 Department of Astronomy, Yunnan University, and Key Laboratory of Astroparticle Physics of Yunnan Province, Kunming, 650091, People’s Republic of China; xiang_yunchuan@yeah.net, zjjiang@ynu.edu.cn
2 School of Physical Science and Technology, Kunming University, Kunming 650214, People’s Republic of China; tangyunyong888@163.com

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Abstract

In this paper, we report the first extended GeV $\gamma$-ray emission, at a significant level of $\sim$8.13$\sigma$, from the region of the supernova remnant SNR G317.3-0.2 by analyzing $\sim$12.2 yr of Fermi Large Area Telescope Pass 8 data in the work. The best-fit position of the new $\gamma$-ray source matches that of the 843 MHz radio energy band of SNR G317.3-0.2, and there is no significant variability of the photon flux of the corresponding light curve in the data for the 12.2 yr period. Therefore, by excluding other known $\gamma$-ray sources or candidates within a 2$\sigma$ error radius from the best-fit position of SNR G317.3-0.2, we suggest that the $\gamma$-ray source is likely to be a GeV counterpart of SNR G317.3-0.2.

Unified Astronomy Thesaurus concepts: Gamma-ray astronomy (628); Non-thermal radiation sources (1119); Supernova remnants (1667); Extended radiation sources (504)

1. Introduction

Whiteoak & Green (1996) reported features at 843 MHz for SNR G317.3-0.2 as a shell supernova remnant (SNR) based on observations performed using the Molonglo Observatory Synthesis Telescope (MOST). SNR G317.3-0.2 consists of two asymmetric and opposing arcs, with a flux of 5.2 Jy. The 843 MHz flux density map showed a strong asymmetry between the southeast lobe and northwest lobe, and the flux density of the southeast lobe was brighter than that of the northwest lobe. Their findings suggested that the diffuse emission of SNR G317.3-0.2 was likely to be associated with the nearby ionized region from H II GAL 316-8.0.1. Its surface luminosity was $5.8 \times 10^{-21}$ W m$^{-2}$ Hz$^{-1}$ s$^{-1}$ at a distance of 9.7 kpc at 1 GHz (Case & Bhattacharya 1998). Stupar & Parker (2011) found an excellent match between the Hα and 4850 MHz radio emissions in the central and southwest region. The evidence suggests that the SNR could be an optical counterpart.

Acero et al. (2016) analyzed the GeV $\gamma$-ray emission of SNR G317.3-0.2 using Fermi Large Area Telescope (Fermi-LAT) data from 2008 August 4 to 2011 August 4. However, they did not find a significant $\gamma$-ray emission. The 95% and 99% confidence upper limits with two power-law spectral indices ($\Gamma = 2.0$ or 2.5) from the region were provided in their work. Thus far, X-ray and TeV energy bands have not been observed precisely for SNR G317.3-0.2.

West et al. (2016) used a physically motivated model, which involves the evolution of the morphology of SNRs in the magnetic field, to simulate the magnetic field distribution of SNR G317.3-0.2 according to its 843 MHz radio morphology. They found a strong asymmetry, and their results resembled the distribution of the 843 MHz flux density. They considered that the asymmetry was likely to be caused by the vector of the magnetic field along the X-axis in a three-dimensional coordinate system. In the magnetic field region where SNRs enter, it can produce radio synchrotron emission with higher intensity, resulting in the bright limbs of SNRs (van der Laan 1962; Whiteoak & Gardner 1968).

With the accumulation of photons, more precise diffuse $\gamma$-ray backgrounds, and an improved data set, we revisit the $\gamma$-ray radiation of SNR G317.3-0.2 by analyzing approximately 12.2 yr of the Fermi-LAT PASS 8 data (Abdollahi et al. 2020). We find the likely GeV $\gamma$-ray radiations from SNR G317.3-0.2. The 843 MHz flux density map with a higher spatial resolution of 43″ of SNR G317.3-0.2 presents a clear and asymmetric structure, which enabled us to better study the spatial distribution of its GeV $\gamma$-ray radiation using the Fermi-LAT analysis method provided by the Fermi Science Support Center. In addition, the highly asymmetric structure of SNR G317.3-0.2 at 843 MHz, which makes it an excellent source for studying the asymmetric evolution of SNR and the unknown origin of cosmic rays in the Milky Way in the future (Aharonian et al. 2004; Helder et al. 2012; Ackermann et al. 2013; Bao et al. 2018; Ferrand et al. 2019; Orlando et al. 2021).

In this paper, the data analysis procedures are introduced in Section 2, and the analysis results are presented in Section 3. The detection and likely origin of GeV radiation are discussed and conclusions are provided in Section 4.

2. Data Reduction

We used Fermi Science Tools version v11r5p3 to perform the analysis. The Pass 8 “Source” event class (evclass = 3 and evclass = 128) and the instrumental response function (IRF) “P8R3_SOURCE_V2” were used to analyze the $\gamma$-ray emission from the source. Events with zenith angles above 90° were excluded to reduce the contamination of the Earth limb. We set the energy range of data recorded from 2008 August 4 to 2020 October 24 (mission elapsed time 239557427–625268550) as 2–500 GeV to avoid a large point-spread function (PSF) and the pollution of the galactic diffuse background in the lower energy band. Region of interest (ROI) was 20° × 20° and was centered at the position

3 Corresponding author.

4 http://fermi.gsfc.nasa.gov/sci/data/analysis
5 http://fermi.gsfc.nasa.gov/sci/data/analysis/software/
R.A. = 222°43, decl. = −59°77 from SIMBAD. Assuming a point source with a power-law spectral model at the location of SNR G317.3-0.2, we calculated its best-fit position to be R.A., decl. = 222.51, −59.75 with a 68% (95%) error circle of 0°046 (0°074) using gtfindsrc, and we replaced the original position of SNR G317.3-0.2 with the best-fit position. Then, we marked the new γ-ray source as SrcX for all subsequent analyses. The script make4FGLxml.py was used to generate the source model file containing all sources within an ROI of 30° around SNR G317.3-0.2 from the Fermi Large Telescope Fourth Source Catalog (4FGL; Abdollahi et al. 2020). Furthermore, a point source with a power-law spectral model in the best-fit position of SrcX was added to the model file. The tool gtlike was used to fit the data by following the data analysis method of the Fermi Science Support Center. All spectral indexes and normalizations from sources within 5° were set as free. Moreover, the normalizations from the Galactic diffuse emission (gll_iem_v07.fits) and the isotropic extragalactic emission (iso_P8R3_SOURCE_V2_v1.txt) were also set as free.

3. Results

In the analysis, we first calculated the test statistic (TS) map, which is a significance map based on the maximum likelihood test statistic, by running gtstatmap centered at the position of SrcX in the 2–500 GeV energy band. We found significant γ-ray radiation with a TS value = 32.46 from the direction of SrcX, as shown in the left panel of Figure 1. We chose to add six point sources (P1–P6) with a power-law spectrum to the position of the local maxima of the TS map within 2°2 to subtract brighter residual radiation in all subsequent analyses. We found that γ-ray radiation was still significant with a TS value of 22.74, as shown in the middle panel of Figure 1. The fitting parameters of P1–P6 are shown in Table 4 (please see the Appendix). After subtracting SrcX, we found that there was no significant residual emission from the location of SrcX, as shown in the right panel of Figure 1. Therefore, we suggest that the γ-ray emission may come from SrcX. We also checked the

Figure 1. Three TS maps with 0°02 pixel size in the 2–500 GeV energy band centered at the position of SrcX marked as a magenta cross in a 2°2 × 2°2 region. Left panel: TS map including all sources from 4FGL. Middle panel: TS map after subtracting P1–P6. Right panel: TS map after subtracting all sources containing SrcX and P1–P6. A Gaussian function with a kernel radius of 0°3 was used to smooth these maps.

Figure 2. Counts map with 0°02 pixel size in the 2–500 GeV energy band centered at the position of SrcX marked as a green cross in the 0°6 × 0°6 region. The panel is smoothed with a Gaussian kernel of 0°3. Two solid and dashed green circles show the 68% and 95% error circles of the best-fit position of SNR G317.3-0.2, respectively. The cyan contours are from observations performed using MOST (SNR G317.3-0.2: Whiteoak & Green 1996). 

2°2 × 2°2 counts map of the ROI using gtbin, as shown in Figure 2, with the SrcX position as the center. Here, we can see that a certain number of photons are distributed at the position of SrcX. Combined with the significant residual emission from the right TS map in Figure 1, we suggest that there likely exists a new high-energy γ-ray source at the location of SrcX.

Here, we checked the γ-ray spatial distribution of SrcX using uniform disk (2D Gaussian) models with different values of radii (σ). Here, the radius (σ) for the uniform disk (2D Gaussian) model is set in the range of 0°1–1°2 with a step of 0°05. The fitting results with the highest TS values from the different spatial models are listed in Table 1. Here, we adopted the Akaike information criterion (AIC; Akaike 1974), which is expressed by the formula \[ \Delta \text{AIC} = \text{AIC}_{\text{point}} - \text{AIC}_{\text{ext}} \], to compare the improvement level of spatial models between the point source and the extended source. The AIC values of the point source and extended source are represented using AIC_{point} and AIC_{ext} respectively. A significantly improved AIC value ≈32.84 was found using the 2D Gaussian spatial...
Figure 3. LC of 20 time bins in the 2–500 GeV energy band for SrcX. The upper limits with the 95% confidence level are given for the time bin with a TS value <4. The time bins with TS values >4 are marked by the gray shaded area. The average photon flux with a maximum likelihood of \(\approx 12.2\) yr is represented by the black solid line, and the two black dashed lines indicate its 1\(\sigma\) statistic uncertainties.

| Spatial Model   | Radius (\(\sigma\)) (deg) | Spectral Index | Photon Flux (10\(^{-9}\) ph cm\(^{-2}\) s\(^{-1}\)) | TS Value | TS\(_{\text{var}}\) | Degrees of Freedom |
|----------------|-----------------------------|----------------|---------------------------------|----------|----------------|------------------|
| Point source   | \(\cdots\)                 | 2.94 \(\pm\) 0.51 | 0.39 \(\pm\) 0.10               | 21.68    | \(\cdots\)    | 4                |
| 2D Gaussian    | 0\(^{\circ}\)60             | 2.12 \(\pm\) 0.15 | 2.56 \(\pm\) 0.36               | 81.25    | 59.57          | 5                |
| Uniform disk   | 0\(^{\circ}\)95             | 2.13 \(\pm\) 0.11 | 1.96 \(\pm\) 0.33               | 66.56    | 44.88          | 5                |

Figure 3. LC of 20 time bins in the 2–500 GeV energy band for SrcX. The upper limits with the 95% confidence level are given for the time bin with a TS value <4. The time bins with TS values >4 are marked by the gray shaded area. The average photon flux with a maximum likelihood of \(\approx 12.2\) yr is represented by the black solid line, and the two black dashed lines indicate its 1\(\sigma\) statistic uncertainties.

### 3.1. Variability Analysis

A light curve (LC) with 20 time bins of \(\sim 12.2\) yr in the 2–500 GeV energy band was generated to check the variability of photon flux from SrcX. The variability was estimated using the variability index TS\(_{\text{var}}\) from the work of Nolan et al. (2012). TS\(_{\text{var}}\) \(\geq 36.19\) was used to identify variable sources at a 99% confidence level for the LC of 20 time bins. However, no significant variability from the photon flux was found from SrcX with TS\(_{\text{var}}\) \(= 27.73\) in the LC, as can be seen from Figure 3.

### 3.2. Spectral Analysis

A source with a TS\(_{\text{curve}}\) > 16 was considered significantly curved, where it is defined as TS\(_{\text{curve}}\) = 2(log L(curved spectrum)–log L(powerlaw)) in Nolan et al. (2012). Here, we tested two frequently used models in 4FGL, LogParabola, and PLSuperExpCutoff2.\(^{11}\) We found TS\(_{\text{curve}}\) \(\approx 0\) and TS\(_{\text{curve}}\) \(\approx 2\) for LogParabola and PLSuperExpCutoff2, respectively. These results indicate that the spectrum of this source is not significantly curved, which is consistent with those of 45 extended sources with the average value of TS\(_{\text{curve}}\) = 3.2.\(^{12}\) Therefore, we chose a simple power-law model as the best spectral model to describe the spectrum of the observation data in this analysis.

Using the binned likelihood analysis method, the photon flux of the global fit for SrcX was found to be \((2.56 \pm 0.36) \times 10^{-9}\) ph cm\(^{-2}\) s\(^{-1}\) with a power-law spectral index of 2.12 \(\pm\) 0.15 in the 2–500 GeV energy band. The 2–500 GeV energy band was selected to generate its spectral energy distribution (SED) with four equal logarithmic bins. Similar to the method of the global fit, each energy bin was independently fitted using gtlike. An upper limit with a 95% confidence level was given for the energy bin with a TS value <4, as shown in Figure 4.

Moreover, the systematic uncertainties from the effective area were calculated using the bracketing Aeff method.\(^{13}\) The systematic uncertainties of the galactic diffuse emission were estimated by artificially fixing the best-fit value of normalization of the galactic diffuse model from each energy bin to a 6% deviation (e.g., Abdo et al. 2009, 2010a, 2010b; Xing et al. 2015; Xin et al. 2018). The best-fit data are presented in Table 2.

### 4. Discussion and Conclusion

#### 4.1. Source Detection

Through the simulation of the spatial distribution of the \(\gamma\)-ray source, we found that the 2D Gauss model with index = 2.12 \(\pm\) 0.15 performs better than a point-source template. For the spectral index range of extended sources, we investigated the Fermi Galactic Extended Source catalog (FGES) from Ackermann et al. (2017) and found that the average value of the spectral index of the extended sources

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\(^{11}\) https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/source_models.html

\(^{12}\) Here, we excluded 4FGL J1825.2-1359 with the LogParabola spectral model from this calculation, so its spectrum with TS\(_{\text{curve}}\) = 21 is significantly different from other extended \(\gamma\)-ray sources in FGES.

\(^{13}\) https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/Aeff_Systematics.html
detected above 10 GeV is 2.16. We found that the value of the spectral index of 2.12 ± 0.15 corresponding to SrcX is close to this value of 2.16, and the power-law spectral characteristic of the new γ-ray source is consistent with those of the extended γ-ray sources from FGES in Section 3.2. In addition, as shown in the left panel of Figure 5, we find that the location of SNR G317.3-0.2 is within a 2σ error radius, and many contours of the 843 MHz southeast lobe are within a 2σ error radius. Meanwhile, SIMBAD and Aladin were used to investigate whether the region within the 2σ error radius of the best-fit position corresponds to the currently known GeV γ-ray sources or candidates such as the pulsar wind nebula, active galactic nuclei (AGN), gamma burst, or other SNRs. However, we did not find a likely match. Therefore, we suggest that the new γ-ray emission is likely to originate from SNR G317.3-0.2.

Currently, most SNRs are considered to be a relatively stable objects in the local universe. They are different from AGNs and do not have short-timescale variability in LCs. As shown in Figure 3, in 12.2 years, the LC exhibited no significant variability with TSvar = 27.73. We then compared the average value of TSvar ≈ 10.58 from 25 SNRs that have been firmly certified in 4FGL and found that the characteristic of no variability of SrcX is consistent with that of most of the SNRs observed in the GeV energy band. This evidence implies that the γ-ray emission of SrcX is more likely to come from SNR G317.3-0.2, and the new γ-ray source is probably the GeV counterpart of SNR G317.3-0.2.

### 4.2. Model Fitting

Generally, two scenarios refer to lepton and hadron, respectively, to explain GeV γ-ray emission production (e.g., Condon et al. 2017; Xing et al. 2019, and references therein):

1. the leptonic scenario, where the γ-ray emission is induced by the inverse Compton scattering of relativistic electrons; and
2. the hadronic scenario, involving the decay of neutral pion produced by proton–proton interactions.

Through the above discussion, in the case of correlation between SNR G317.3-0.2 and SrcX, for the leptonic scenario, we assume that the population of electrons is given by the formula expressed using a power law with an exponential cutoff (PLEC) as follows (e.g., Aharonian et al. 2006; Xin et al. 2019):

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

where \( N_0 \) is the amplitude, \( E \) is the particle energy, \( \alpha \) is the spectral index, \( E_{\text{cutoff}} \) is the break energy, and \( E_0 \) is fixed to 1 TeV. Here, we consider using a simple one-zone stationary model from NAIMA (Zabalza 2015, and references therein) to
explain the Fermi-LAT observations in this work. The value of the distance of SNR G317.3-0.2 was adopted to be 9.5 kpc (Guseinov et al. 2004). We found that the data can be explained well with a reduced $\chi^2$ value of 0.01. The best-fit results are presented in Table 3.

For the hadronic scenario, we first investigated the OH maser emission at 1720 MHz around SNR G317.3-0.2 as convincing evidence for verifying the interaction of SNRs with molecular clouds. However, no significant OH maser emission was found by Frail et al. (1996). Moreover, for the case of interactions between the relativistic protons and the surrounding CO gas molecules from the SNR, we investigated the observation results from the 1.2 m millimeter-wave (CfA) telescope at the Harvard–Smithsonian Center for Astrophysics (Dame et al. 2001) and found that the molecular cloud in this region is very dense. However, due to a low angular resolution of ~8.5¢ at 115 GHz of the CfA telescope, the interactions from relativistic protons and CO gas molecules are uncertain thus far. For the uncertain origin of the $\gamma$-ray emission from the region, we also chose to consider the hadronic scenario (e.g., Condon et al. 2017; Zeng et al. 2017, 2019; Xing et al. 2019). Here, we considered the three different gas densities, $n_{\text{gas}} = 1$ cm$^{-3}$, 10 cm$^{-3}$, and 100 cm$^{-3}$, to explain the Fermi-LAT observations, with the population of protons given by Equation (1).

Furthermore, PYTHIA 8, as a toolkit referring to the cross-section of the proton-proton energy losses and pion production (Kafexhiu et al. 2014), was used to fit the data of SNR G317.3-0.2. Similar to the leptonic model, we find that the data can be also explained well with the same reduced $\chi^2$ value of ~0.2 using the three hadronic models with different gas densities, as shown in the right panel of Figure 6.

### 4.3. Summary

We analyzed the $\gamma$-ray radiation from the region of SNR G317.3-0.2 using the latest Fermi-LAT Pass 8 data and found that its photon flux was $(2.56 \pm 0.36) \times 10^{-9}$ ph cm$^{-2}$ s$^{-1}$ with $\sim 8.13\sigma$ in the 2–500 GeV energy band. Further, we found that its spectral characteristic, which has a spectral index of $2.12 \pm 0.15$ with the power-law spectrum, is in good agreement with those of other extended sources. Meanwhile, the 2D Gaussian $\gamma$-ray spatial distribution showed better improvement than other spatial models by AIC. Its spatial position coincided well with that of the 843 MHz radio band, and no other known GeV $\gamma$-ray sources or candidates were found in the region of SNR G317.3-0.2. We also analyzed the variability of the LC in ~12.2 yr and found that there was no significant variability of photon flux, which implies that the characteristic of no variability of its LC is in good agreement with the SNRs observed thus far. Therefore, we suggest that the new $\gamma$-ray

### Table 3

| Model Name | $n_{\text{gas}}$ (cm$^{-3}$) | $\alpha$ | $E_{\text{cutoff}}$ (TeV) | $W_\gamma$ (or $W_p$) (10$^{39}$ erg) | $\chi^2$/N$_{\text{dat}}$ |
|------------|-----------------|---------|-----------------|-----------------|-------------------|
| Leptonic model | ⋯ | 2.07$^{+0.56}_{-0.94}$ | 0.96$^{+0.42}_{-0.27}$ | 3.99$^{+0.63}_{-0.66}$ | 0.006$^{+0.2}_{-0.3}$ = 0.01 |
| Hadronic model | 1 | 2.14$^{+0.21}_{-0.24}$ | 10.1$^{+1.3}_{-1.49}$ | 394.1$^{+76.2}_{-71.7}$ | 0.1$^{+0.1}_{-0.2}$ = 0.20 |
| Hadronic model | 10 | 2.26$^{+0.24}_{-0.31}$ | 9.77$^{+1.62}_{-1.29}$ | 28.4$^{+9.0}_{-4.38}$ | 0.09$^{+0.07}_{-0.2}$ = 0.18 |
| Hadronic model | 100 | 2.14$^{+0.27}_{-0.35}$ | 9.93$^{+0.58}_{-1.50}$ | 3.57$^{+3.4}_{-0.66}$ | 0.1$^{+0.1}_{-0.2}$ = 0.20 |

Note. The upper limit of the fourth bin is taken into account in the fit (e.g., Abdalla et al. 2018). For the values of $W_\gamma$ (or $W_p$) with electronic (or protonic) kinetic energy of above 2 GeV, first, we fixed the best-fitting values of the rest of the parameters and finally independently fitted $W_\gamma$ (or $W_p$).
source is probably the GeV counterpart of SNR G317.3-0.2. Moreover, the leptonic and hadronic models with the same PLEC particle population could well explain the GeV radiation spectrum in the 2–500 GeV energy band, independently.

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Appendix

Table 4 contains relative fitting information from the six point sources added in Section 3.

**ORCID iDs**

Yunchuan Xiang @ https://orcid.org/0000-0001-7985-4129
Zejun Jiang @ https://orcid.org/0000-0002-4705-2479

Yunyong Tang @ https://orcid.org/0000-0002-1334-828X

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