Detection of GeV Gamma-Ray Emission in the Direction of HESS J1731-347 with Fermi-LAT

Xiao-Lei Guo¹², Yu-Liang Xin¹³, Neng-Hui Liao¹², Qiang Yuan¹², Wei-Hong Gao⁴⁵, and Yi-Zhong Fan¹²

¹ Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, People’s Republic of China; ylxin@pmo.ac.cn, yuanq@pmo.ac.cn
² School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026, Anhui, People’s Republic of China
³ University of Chinese Academy of Sciences, Yuquan Road 19, Beijing, 100049, People’s Republic of China
⁴ Department of Physics and Institute of Theoretical Physics, Nanjing Normal University, Nanjing 210046, People’s Republic of China; gaoweihong@nju.edu.cn
⁵ INAF-Osservatorio Astronomico di Brera, via E. Bianchi 46, 23807 Merate, Italy

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Abstract

We report the detection of GeV γ-ray emission from supernova remnant HESS J1731-347 using 9 yr of Fermi Large Area Telescope data. We find a slightly extended GeV source in the direction of HESS J1731-347. The spectrum above 1 GeV can be fitted by a power law with an index of $\Gamma = 1.77 \pm 0.14$, and the GeV spectrum connects smoothly with the TeV spectrum of HESS J1731-347. Either a hadronic–leptonic or a pure leptonic model can fit the multiwavelength spectral energy distribution of the source. However, the hard GeV γ-ray spectrum is more naturally produced in a leptonic (inverse Compton scattering) scenario, under the framework of diffusive shock acceleration. We also searched for the GeV γ-ray emission from the nearby TeV source HESS J1729-345. No significant GeV γ-ray emission is found, and upper limits are derived.

Key words: gamma rays: general – gamma rays: ISM – ISM: individual objects (HESS J1731-347) – ISM: supernova remnants

1. Introduction

It is widely believed that supernova remnants (SNRs) are the main accelerators of Galactic cosmic rays (CRs) with energies up to the knee. This is supported by the nonthermal X-ray emission detected in many SNRs, which indicates the acceleration of electrons to hundreds of TeV energies (e.g., Koyama et al. 1995). The GeV and/or TeV γ-rays have also been detected in some SNRs, for example, RCW 86 (Aharonian et al. 2009; Yuan et al. 2014), Cas A (Albert et al. 2007a; Abdo et al. 2010a), CTB 37B (Aharonian et al. 2008b; Xin et al. 2016), Puppis A (Hewitt et al. 2012; Xin et al. 2017), IC 443 (Albert et al. 2007b; Acciari et al. 2009; Ackermann et al. 2013), and W44 (Abdo et al. 2010b; Ackermann et al. 2013). Gamma rays can be produced by the decay of neutral pions due to the inelastic pp collisions (the hadronic process), the inverse Compton scattering, or the bremsstrahlung process of relativistic electrons (the leptonic process). For some SNRs interacting with dense molecular clouds, the evidence for acceleration of nuclei has been suggested by GeV/TeV γ-ray observations (Li & Chen 2010; Ackermann et al. 2013). HESS J1731-347 (G353.6-0.7) was first observed as an unidentified very high energy (VHE; $>100\text{ GeV}$) γ-ray source by the High Energy Stereoscopic System (HESS) (Aharonian et al. 2008a). Tian et al. (2008) discovered the radio and X-ray counterparts of HESS J1731-347 and identified it as a shell-type SNR. Abramowski et al. (2011) carried out an additional γ-ray observation with HESS and detected its shell-type morphology. Together with RX J1713.7-3946 (Aharonian et al. 2004, 2006, 2007a), RX J0852.0-4622 (Aharonian et al. 2005, 2007b), RCW 86 (Aharonian et al. 2009; Abramowski et al. 2016), and SN 1006 (Acero et al. 2010), HESS J1731-347 becomes one of five firmly identified TeV shell-type SNRs (Rieger et al. 2013).

The distance of HESS J1731-347 is under debate. Tian et al. (2008) argued that HESS J1731-347 is located at $\sim 3.2\text{ kpc}$ if it is associated with the nearby H II region G353.42-0.37. By comparing the absorption column density derived from the X-ray observation and that obtained from $^{12}\text{CO}$ and $\text{H}_1$ observations, Abramowski et al. (2011) set $3.2\text{ kpc}$ as a lower limit of its distance, which is reinforced by Doroshenko et al. (2017). In addition, Fukuda et al. (2014) suggested that HESS J1731-347 is correlated with the interstellar proton cavity at a velocity range from $-90$ to $-75\text{ km s}^{-1}$, indicating a distance of $5.2-6.1\text{ kpc}$. However, no significant emission from dense molecular gas traced by the CS $(1-0)$ line coincides with HESS J1731-347 at that distance (Maxted et al. 2018). Due to uncertainties of the distance and other parameters, the age of HESS J1731-347 is estimated to be in a wide range of $2-27\text{ kyr}$ (Tian et al. 2008; Abramowski et al. 2011; Fukuda et al. 2014; Acero et al. 2015b).

HESS J1731-347 and its subregions were detected in the X-ray band by ROSAT, XMM-Newton, and Suzaku, with an X-ray morphology consistent with the radio shell (Tian et al. 2008, 2010; Abramowski et al. 2011; Bamba et al. 2012; Doroshenko et al. 2017). The X-ray emission from the complete SNR and its subregions is found to be nonthermal. The X-ray spectral index is $2.28$ for the northeast region (Abramowski et al. 2011). A compact object, XMM S J173203-344518, located near the geometrical center of the remnant, was detected by XMM-Newton, which was considered to be the central compact object associated with HESS J1731-347 (Tian et al. 2010; Halpern & Gotthelf 2010; Abramowski et al. 2011).

Yang et al. (2014) and Acero et al. (2015b) searched for the GeV γ-ray emission from HESS J1731-347 with the Fermi Large Area Telescope (Fermi-LAT; Atwood et al. 2009) data. No significant signal was detected, and only the upper limits
were given. Furthermore, no candidate source in the third Fermi-LAT source catalog (3FGL; Acero et al. 2015a) is found to be associated with HESS J1731-347.

In this paper, we revisit the GeV γ-ray emission in the direction of HESS J1731-347, with 9 yr Pass 8 data recorded by Fermi-LAT. A statistically significant excess that is positionally consistent with HESS J1731-347 is found. In Section 2, we present the data analysis and results, including the spatial and spectral analysis. Based on the multiwavelength observations of HESS J1731-347, we model the nonthermal radiation of it in Section 3. The conclusion of this work is presented in Section 4.

2. Data Analysis

2.1. Data Reduction

We select the latest Pass 8 version of the Fermi-LAT data with “Source” event class (evclass = 128 and evtype = 3), recorded from 2008 August 4 (Mission Elapsed Time 239557418) to 2017 August 4 (Mission Elapsed Time 523497605). The region of interest is chosen to be a 14° × 14° box centered at HESS J1731-347. In order to have a good angular resolution, we adopt the events with energies between 1 and 300 GeV in this analysis. In addition, the events whose zenith angles are larger than 90° are excluded to reduce the contamination from the Earth limb. The data are analyzed with the Fermi-LAT Science Tools v10r0p5 and the standard binned likelihood analysis method gtlike. The diffuse backgrounds used are gll_iem_v06.fits and iso_P8R2_SOURCE_V6_v06.txt, which can be found from the Fermi Science Support Center. All sources listed in the 3FGL and the two diffuse backgrounds are included in the model. During the fitting procedure, the spectral parameters and the normalizations of sources within 5° around HESS J1731-347, together with the normalizations of the two diffuse backgrounds, are left free.

2.2. Results

We create a 4° × 4° TS (test statistic, which is essentially the logarithmic likelihood ratio between different models) map centered at HESS J1731-347 by slicing the center of the box along each axis, after subtracting the 3FGL sources and the diffuse backgrounds. There are still excesses in this TS map, as marked by green plus signs. At the center of the TS map, a weak excess (labeled as Source T) is found to be spatially coincident with HESS J1731-347. It is noted that Newpts C was also detected in Yang et al. (2014), with a TS value of about 20. We add Source T and the other six new sources, from A to F, in the model as additional point sources with power-law (PL) spectra, and we redo the likelihood fitting. The positions of these new sources are optimized by the gtfindsrc tool. Best-fitting results of their coordinates and TS values are listed in Table 1. The TS value of Source T is about 25.9, and its best-fitting position is R.A. = 262°502, decl. = −34°775 with a 1σ error circle of 0°022. The residual TS map after subtracting the additional sources A to F is shown in the right panel of Figure 1.

| Name       | R.A. (deg) | Decl. (deg) | TS  | Δθ (deg) |
|------------|------------|-------------|-----|----------|
| Source T   | 262.902    | −34.775     | 25.9| 0.093    |
| Newpts A   | 264.048    | −34.370     | 130.8| 0.936    |
| Newpts B   | 262.629    | −33.882     | 29.3| 0.929    |
| Newpts C   | 262.280    | −35.051     | 59.8| 0.670    |
| Newpts D   | 260.867    | −33.704     | 59.5| 2.062    |
| Newpts E   | 262.266    | −36.233     | 34.9| 1.598    |
| Newpts F   | 265.161    | −34.500     | 26.5| 1.786    |

2.2.1. Spatial Extension

Considering that HESS J1731-347 has an extended morphology in radio, X-ray, and TeV γ-ray bands, we carried out an extension test with different spatial models. We used a uniform disk centered at the best-fitting position of Source T with radii of 0°1, 0°15, 0°2, and 0°25, as well as the TeV γ-ray image of HESS J1731-347, as spatial templates of Source T. The TS values for different spatial models are listed in Table 2. We found that a 0°15 disk template gives the highest TS value, 33.9, which corresponds to a significance of ∼4.7σ for 5 (2 for the coordinates, 1 for the radius, and 2 for the spectrum) degrees of freedom (doF). For the four adopted disk templates, the TS values do not differ much from each other. Compared with the point-source hypothesis, the data favor slightly an extended morphology. Using the TeV γ-ray template, a TS value of 25 is found. These results are quite consistent with those of Condon et al. (2017), which used the data with different energy ranges and observation time series. In the following analysis, we adopt the 0°15 disk template for Source T.

We also try to search for γ-ray emission from the nearby TeV source HESS J1729-345. The TeV image of HESS J1729-345 is used as the spatial template. No significant GeV γ-ray emission from the direction of HESS J1729-345 is detected. The TS value of HESS J1729-345 is about 4, and its flux upper limits will be derived (see the next subsection).

2.2.2. Spectral Analysis

For Source T, the global fit in the 1−300 GeV energy range with a 0°15 disk template gives a spectral index of Γ = 1.77 ± 0.14 and an integral photon flux of (6.92 ± 2.06) × 10−10 photons cm−2 s−1 with statistical errors only. Assuming a distance of 3.2 kpc (Tian et al. 2008; Nayaka et al. 2017), the γ-ray luminosity between 1 and 300 GeV is 1.26 × 1034 (d/3.2 kpc)2 erg s−1.

The data are further divided into four energy bins with equal width in the logarithmic space to study its spectral energy distribution (SED). For each energy bin, we repeat the likelihood analysis, with only the normalizations of the sources and its relationship with HESS J1731-347. The GeV γ-ray emission overlaps with part of the VHE emission region shown by the contours (Abramowski et al. 2011). However, the GeV TS map does not fully overlap with the TeV image, which is possibly due to the large point-spread function (PSF) of Fermi-LAT and/or the fluctuation of the weak signal. Similar cases were also shown for SN 1006 (Xing et al. 2016) and HESS J1534-571 (Araya 2017).
within 5° around Source T and the diffuse backgrounds in the model free. The spectral parameters of these sources are fixed to be the best-fitting values obtained in the global likelihood analysis. If the TS value of Source T is smaller than 4 in an energy bin, a 95% confidence level upper limit is given. The GeV SED connects smoothly with the TeV spectrum of HESS J1731-347. The spatial coincidence and a smoothly connected γ-ray spectrum suggest that Source T is the GeV counterpart of HESS J1731-347.

The signficance of HESS J1729-345 is not high enough, and we derive the flux upper limits in energy bins of 1−6.7 GeV, 6.7−44.8 GeV, and 44.8−300 GeV, which are shown in Figure 4.

3. Discussion

The radio counterpart of HESS J131-347 was first identified by Tian et al. (2008). The integrated flux density was derived to be $2.2 \pm 0.9$ Jy at 1420 MHz, through extrapolating that of one-half of the remnant at low Galactic latitudes to the total SNR. With the Giant Metrewave Radio Telescope, Nayana et al. (2017) observed the complete shell of HESS J131-347 at 325 MHz and obtained an integrated flux density of $1.84 \pm 0.15$ Jy. In the following models, we use the results of the SED are shown in Figure 3. The GeV SED connects smoothly with the TeV spectrum of HESS J1731-347. The spatial coincidence and a smoothly connected γ-ray spectrum suggest that Source T is the GeV counterpart of HESS J1731-347.

The significance of HESS J1729-345 is not high enough, and we derive the flux upper limits in energy bins of 1−6.7 GeV, 6.7−44.8 GeV, and 44.8−300 GeV, which are shown in Figure 4.
of Nayana et al. (2017) to constrain the model parameters. The X-ray flux of the full SNR given by Doroshenko et al. (2017) is also used.

We assume either a pure leptonic model or a hadronic–leptonic hybrid one to fit the wide-band SED from radio to TeV γ-rays. The spectrum of electrons or protons is assumed to be an exponential cutoff power-law form

\[ \frac{dN}{dE} \propto E^{-\alpha_i} \exp\left[\frac{-(E/E_{c,i})}{\delta}\right], \]

where \( i = e \) or \( p \), \( \alpha_i \) is the spectral index, and \( E_{c,i} \) is the cutoff energy of particles. \( \beta \) describes the sharpness of the cutoff, \( \delta \) describes the sharpness of the cutoff, and we adopt the typical values of 0.5, 0.6, and 1.0 to constrain the parameters in the model. The radius of the SNR is nearly 0.25 in the radio band (Tian et al. 2008; Nayana et al. 2017) and 0.27 in the TeV band (Abramowski et al. 2011). Such an angular size corresponds to a physical radius of about 14–15 pc for a distance of 3.2 kpc.

The gas density in the vicinity of HESS J1731-347 is quite uncertain, owing to the lack of thermal X-ray emissions. We assume a nominal value of \( n = 1.0 \, \text{cm}^{-3} \).

For the leptonic model, the background radiation field considered includes the cosmic microwave background and an infrared (IR) radiation field with a temperature of 40 K and an energy density of 1 eV cm\(^{-3}\) (Abramowski et al. 2011). The magnetic field strength is taken as a free parameter, which is determined through fitting to the multiwavelength data. The derived model parameters are given in Table 3. The corresponding multiwavelength SED of the model calculation is shown in the left panel of Figure 5.

The leptonic models with the three different values of \( \delta \) can reproduce the multiwavelength SED with little differences. Compared with the results of Yang et al. (2014), the spectral index of electrons \( \alpha_e \) and cutoff energy \( E_{c,e} \) are both slightly smaller in this work. This may be due to the updated radio, X-ray, and GeV data we used in the model. The magnetic field strength, \( B \sim 28 \, \mu G \), is consistent with that given in Yang et al. (2014). Such a magnetic field strength is slightly larger than that of several other SNRs that show similar GeV–TeV γ-ray spectra, e.g., RX J1713.7-3946 (Abdo et al. 2011; Yuan et al. 2011; Zeng et al. 2017), RX J0852-4622 (Vela Junior; Tanaka et al. 2011), and RCW 86 (Yuan et al. 2014). These SNRs are believed to be a class of sources with leptonic origin of the γ-ray emission (Yuan et al. 2012; Funk 2015; Guo et al. 2017).

The cutoff of the spectrum may be due to the (synchrotron) cooling of electrons. The synchrotron cooling timescale of HESS J1731-347 is estimated to be

\[ t_{\text{syn}} \approx 1800 \left( \frac{E_{c,e}}{9 \, \text{TeV}} \right)^{-1} \left( \frac{B}{28 \, \mu G} \right)^{-2} \, \text{yr}. \]

This timescale is close to the minimum value of the age of HESS J1731-347 inferred with other methods (Tian et al. 2008; Abramowski et al. 2011; Fukuda et al. 2014; Acero et al. 2015b).

Nayana et al. (2017) reported an anticorrelation between the TeV γ-ray emission and radio brightness profile and ascribed such an anticorrelation to the synchrotron cooling effect with a nonuniform magnetic field. This result supports the leptonic scenario for the multiwavelength emission of HESS J1731-347.

The right panel of Figure 5 shows the multiwavelength SED of the hadronic–leptonic hybrid model, in which the radio to X-ray data are accounted for by the synchrotron emission of electrons and the GeV–TeV γ-ray emission is produced by the decay of neutral pions from pp collisions. The model parameters are also summarized in Table 3. For the hybrid models with different values of \( \delta \), a hard spectral index of protons with \( \alpha_p \sim 1.7 \), or even \( \alpha_p \sim 1.5 \), is needed to explain the hard GeV γ-ray spectrum. However, such a spectrum of protons is difficult to produce in the conventional diffusive shock acceleration model of strong shocks. The total energy of protons above 1 GeV is estimated to be \( W_p \sim 1.5 \times 10^{50} \, (n/1.0 \, \text{cm}^{-3})^{-1} \, (d/3.2 \, \text{kpc})^{-1} \, \text{erg} \), corresponding to \sim 15% particle acceleration efficiency for a typical total energy of \( E_{\text{SN}} \sim 10^{51} \, \text{erg} \) released by a core-collapse supernova. The total energy \( W_p \) depends on the distance and ambient gas density of HESS J1731-347. Since there is no thermal X-ray emission observed, the gas density would be very low (e.g., Abramowski et al. 2011) derived an upper limit of gas density.
The total energy of relativistic particles, $W_{cr}$, is calculated for $E > 1$ GeV.

![Figure 5. Modeling of the multiwavelength SED of HESS J1731-347. The left panel is for the leptonic model, and the right panel is for the hadronic–leptonic hybrid model. The models with $\delta = 0.5, 0.6,$ and 1.0 are presented by the dark-yellow, purple, and black solid lines, respectively. The dashed and dotted lines with different colors represent the different radiation components for the model of $\delta = 1.0$. The observational data of the radio (magenta for Nayana et al. 2017; green for Tian et al. 2008), X-rays (Doroshenko et al. 2017), TeV $\gamma$-rays (Abramowski et al. 2011), and GeV $\gamma$-rays presented in this work are shown.](https://example.com/figure5.png)

A spatial correlation between the TeV $\gamma$-ray shell and the interstellar protons at a distance of $\sim 5.2$ kpc was reported in Fukuda et al. (2014). It was suggested that the hadronic process contributes a large fraction of the $\gamma$-ray emission of HESS J1731-347 (Fukuda et al. 2014). This is similar to the cases of RX J1713.7-3946 and RX J0852.0-4622 (Fukui et al. 2012; Fukui 2013; Gabici & Aharonian 2014). However, no significant emission from dense molecular gas at such a distance was detected by Maxted et al. (2018), which seems to be a challenge to the hadronic scenario.

HESS J1729-345 is an unidentified TeV source near HESS J1731-347 (Abramowski et al. 2011). Assuming that HESS J1731-347 locates at a distance of $\sim 3.2$ kpc, Cui et al. (2016) suggested that the TeV $\gamma$-ray emission of HESS J1729-345 possibly originates from the nearby molecular clouds illuminated by the CRs that escaped from HESS J1731-347. Capasso et al. (2016) reported a good spatial coincidence between the TeV $\gamma$-ray image in the bridge region and the dense gas at a distance of 3.2 kpc, which further supports the scenario of Cui et al. (2016). Nayana et al. (2017) detected possible radio counterparts of HESS J1729-345 at 843 MHz and 1.4 GHz. However, the multiwavelength data of HESS J1729-345 are still lacking. Future multiwavelength observations are needed to explore its nature.

### 4. Conclusion

In this paper, we report the GeV $\gamma$-ray emission from the direction of HESS J1731-347 at a significance level of $\sim 4.7 \sigma$, with 9 yr of Pass 8 data recorded by the Fermi-LAT. The spatial morphology of HESS J1731-347 is found to be slightly extended in the GeV band. The GeV spectrum can be described by a hard power-law form with an index of $\Gamma = 1.77 \pm 0.14$.

The $\gamma$-ray characteristics of HESS J1731-347 are similar to those of several shell-type SNRs, including RX J1713.7-3946, RX J0852-4622, RCW 86, and SN 1006. A pure leptonic model can account for the wide-band SED of HESS J1731-347. If the hadronic process is adopted to explain the $\gamma$-ray emission, a very hard ($\sim 1.6$) proton spectrum is required. In addition, the energy budget of CR protons may be a problem, given the potentially low gas density environment implied by the lack of thermal X-ray emission.

We also search for GeV $\gamma$-ray emission from the nearby source HESS J1729-345. No significant excess is detected in its direction, and the upper limits are given. More multiwavelength observations are necessary to address its emission mechanism and test the proposed scenario of the interaction between CRs that escaped from HESS J1731-347 and the molecular clouds.
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ORCID iDs
Yu-Liang Xin https://orcid.org/0000-0001-5135-5942
Neng-Hui Liao https://orcid.org/0000-0001-6614-3344
Yi-Zhong Fan https://orcid.org/0000-0002-8966-6911

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