Fermi Large Area Telescope Observation of Supernova Remnant S147

J. Katsuta1, Y. Uchiyama1, T. Tanaka1, H. Tajima1, K. Bechtol1, S. Funk1, J. Lande1, J. Ballet3, Y. Hanabata4, M. Lemoine-Goumard5,6, and T. Takahashi6

1 W. H. Hansen Experimental Physics Laboratory, Kavli Institute for Particle Astrophysics and Cosmology, Department of Physics and SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94305, USA; katsuta@slac.stanford.edu, uchiyama@slac.stanford.edu
2 Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya 466-8601, Japan
3 Laboratoire AIM, CEA-IRFU/CNRS/Université Paris Diderot, Service d’Astrophysique, CEA Saclay, 91191 Gif sur Yvette, France
4 Department of Physical Sciences, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan
5 Université Bordeaux 1, CNRS/IN2p3, Centre d’Études Nucléaires de Bordeaux Gradignan, 33175 Gradignan, France
6 Institute of Space and Astronautical Science, Japanese Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan

Received 2011 December 14; accepted 2012 April 17; published 2012 June 5

ABSTRACT

We present an analysis of gamma-ray data obtained with the Large Area Telescope on board the Fermi Gamma-ray Space Telescope in the region around supernova remnant (SNR) S147 (G180.0−0.1, 71.7). A spatially extended gamma-ray source detected in an energy range of 0.2−10 GeV is found to coincide with SNR S147. We confirm its spatial extension at >5σ confidence level. The gamma-ray flux is (3.8 ± 0.6) × 10−8 photons cm−2 s−1, corresponding to a luminosity of 1.3 × 1034 (d/1.3 kpc)2 erg s−1 in this energy range. The gamma-ray emission exhibits a possible spatial correlation with the prominent Hα filaments of SNR S147. There is no indication that the gamma-ray emission comes from the associated pulsar PSR J0538 + 2817. The gamma-ray spectrum integrated over the remnant is likely dominated by the decay of neutral π mesons produced through the proton−proton collisions in the filaments. The reacceleration of the pre-existing cosmic rays and subsequent adiabatic compression in the filaments is sufficient to provide the energy density required of high-energy protons.

Key words: acceleration of particles – ISM: individual objects (S147) – radiation mechanisms: non-thermal

Online-only material: color figures

1. INTRODUCTION

GeV gamma-ray sources associated with middle-aged supernova remnants (SNRs) that interact with molecular clouds have recently been discovered with the Large Area Telescope (LAT) on board the Fermi Gamma-ray Space Telescope (Abdo et al. 2009, 2010a, 2010b, 2010c; Castro & Slave 2010). The GeV emission of these SNRs is plausibly dominated by the decay of π0 mesons created by proton−proton collisions, although a dominant electron bremsstrahlung component is an alternative interpretation (Abdo et al. 2009). The SNRs interacting with the molecular clouds are more luminous gamma-ray sources (∼1035–1036 erg s−1 in the LAT band) than other types of SNRs (see Thompson et al. 2011). The observed luminosity requires a high-density gas so that the collisions between the relativistic particles and the target gas become efficient enough, which is easily explained by the interactions with the molecular clouds. Two different types of scenarios are put forward to explain the bright gamma-ray emission. One scenario explains the gamma rays as the π0-decay emission due to the interactions between the nearby molecular clouds and the relativistic protons escaping from the SNR system (Aharontian & Atoyan 1996). Another scenario considers the π0-decay emission from the shock-compressed clouds in a middle-aged SNR, where the accelerated particles frozen in the shocked clouds efficiently collide with the target gas (Uchiyama et al. 2010).

Recently, GeV gamma-ray emission from the Cygnus Loop, a middle-aged remnant without a clear signature of interactions with the molecular clouds, has been detected with the Fermi LAT (Katagiri et al. 2011). The gamma-ray luminosity is quite low (∼1035 erg s−1) compared with the SNRs that do interact with the molecular clouds. The gamma-ray emission can be interpreted as coming from a diffuse gas behind the blast wave, but the dense optical filaments seen in an Hα image would also offer a plausible site for the gamma-ray production. Detections of other low-luminosity SNRs with the Fermi LAT, thanks to an ever-increasing exposure time, will help understand the gamma-ray production sites and constrain cosmic-ray (CR) acceleration in such SNRs.

SNR S147 (G180.0−0.1; hereafter referred to as S147), located toward the Galactic anticenter, is one of the most evolved SNRs in our Galaxy. S147 has a nearly circular shape with an angular diameter of ∼200′. It contains a complex network of long filaments in the optical band (Lozinskaya 1976; Drew et al. 2005) that are also visible in the radio band (Kundu et al. 1980; Sofue et al. 1980; Xiao et al. 2008). These observations also show that the radio and Hα emissions correlate very well. The velocity of the optical filaments is estimated to be 80–120 km s−1 (Lozinskaya 1976; Kirshner & Arnold 1979; Phillips et al. 1981). No indication of interactions with the molecular clouds has been reported.

The radio flux density is 70 Jy at 1 GHz, and the radio spectrum is known to have a spectral break around 1.5 GHz. Xiao et al. (2008) obtained the integrated spectrum of S147 in the 0.1−5 GHz range, and they determined the spectral indices α ∼ 0.3 ± 0.15 and α ∼ 1.20 ± 0.3 below and above the spectral break, respectively. Xiao et al. (2008) also found that the filamentary and diffuse emission in S147 have different spectral indices of α ∼ 0.35 and ∼1.35, respectively, in the frequencies of 2.6–4.8 GHz (above the break). The radio emission is considered to be synchrotron radiation from high-energy electrons, while the origin of the spectral break is uncertain. No X-ray emission has been reported to date from this region (Sauvageot et al. 1990) nor has any TeV emission. The

Funded by contract ERC-StG-259391 from the European Community.
EGRET detected a GeV gamma-ray source (3EG J0542+2610) in the vicinity of S147, but its association with the SNR was unclear due to its large positional uncertainty (0:70 at 95% confidence level; Hartman et al. 1999).

PSR J0538+2817 is plausibly associated with S147 and is located near the center of the SNR (Ng et al. 2007). The pulsar has a spin period of 143 ms and a spin-down luminosity of \(5 \times 10^{34} \text{ erg s}^{-1}\). It was first discovered in the radio band (Anderson et al. 1996) and was later also found in the X-rays (McGowan et al. 2003). The X-ray observation also revealed an extended emission that was indicative of a pulsar wind nebula (PWN; Romani & Ng 2003). Estimated pulsar ages significantly differ between a kinematic age of \(~3 \times 10^4\text{ yr}\) (Kramer et al. 2003) and a characteristic age of \(6 \times 10^5\text{ yr}\) (Anderson et al. 1996). The kinematic age of the pulsar is broadly consistent with estimates of the SNR age, which are in the range of \((2-10) \times 10^4\text{ yr}\) (Sofue et al. 1980; Kundu et al. 1980).

The distance to the SNR is likely to be \(d = 1.3\text{ kpc}\) given a plausible association with the pulsar PSR J0538+2817. The distance to the pulsar is estimated to be \(1.30^{+0.22}_{-0.16}\text{ kpc}\) from the parallax (Chatterjee et al. 2009) and \(1.2 \pm 0.2\text{ kpc}\) with a dispersion measure (Cordes & Lazio 2002). On the contrary, \(d < 0.88\text{ kpc}\) is suggested by the absorption lines of the B1e star HD36665, which originates in gas that is associated with S147 (Phillips et al. 1981; Sallmen & Welsh 2004). The diameter of the SNR is \(D \simeq 76 (d/1.3\text{ kpc}) \text{ pc}\).

Here, we report the LAT observations of SNR S147. A GeV gamma-ray source that spatially coincides with S147 is designated as 1FGL J0538.6+2717 in the Fermi LAT First Source Catalog (1FGL catalog) published by the Fermi LAT Collaboration (Abdo et al. 2010d). In this paper, we present a detailed analysis of this LAT source with a much longer accumulation time of about 31 months. This paper is organized as follows. In Section 2, the observations with the Fermi LAT and the data reduction are summarized. Analysis of the LAT source in the direction of S147 is reported in Section 3, establishing an association between the gamma-ray source and S147. In Section 4, we present the modeling of the gamma-ray emission coming from S147 and discuss its implications to the CR acceleration in middle-aged SNRs.

2. OBSERVATION AND DATA REDUCTION

The Fermi Gamma-ray Space Telescope was launched on 2008 June 11. The LAT on board Fermi is a pair conversion telescope that is equipped with solid-state silicon trackers and cesium iodide calorimeters, which are sensitive to photons in a broad energy band from 0.02 to >300 GeV. The LAT has a large effective area (~8000 cm\(^2\) above 1 GeV for on-axis events), instantaneously viewing ~2.4 sr of the sky with a good angular resolution (68% containment radius better than ~1\(^\circ\) above 1 GeV). Details of the LAT instrument and data reduction are described in Atwood et al. (2009).

The LAT data used here were collected for about 31 months from 2008 August 4 to 2011 March 1. The Diffuse event class was chosen and photons beyond the earth zenith angle of 105\(^\circ\) were excluded to reduce the background from the Earth limb. The P6_V11\(^a\) instrument response functions were used for the analyses in this paper.

\(^a\) http://www.slac.stanford.edu/exp/glast/groups/canda/archive/pass6v11/lat_Performance.htm.

3. ANALYSIS AND RESULTS

We utilized gtlike in the Science Tools analysis package\(^9\) for spectral fits. With gtlike, a binned maximum likelihood fit is performed on the spatial and spectral distributions of observed gamma rays to optimize spectral parameters of the input model taking into account the energy dependence of the point-spread function (PSF).

Analysis using gtlike is performed in a \(17^\circ \times 17^\circ\) region around S147, which is referred to as a region of interest (ROI). The fitting model includes other point sources whose positions are given in the 1FGL catalog.\(^10\) Since the nearby SNR IC443 is spatially resolved by the LAT, we model its spatial distribution as a disk centered at \((\alpha, \delta) = (94:31, 22:58)\) with a diameter of 48\(^\circ\) according to Abdo et al. (2010b). The Galactic diffuse emission is modeled by “gll_iem_v02_P6_V11_DIFFUSE.fit” and an isotropic component (instrumental and extragalactic diffuse backgrounds) by “isotropic_iem_v02_P6_V11_DIFFUSE.txt.” Both background models are the standard diffuse emission models released by the LAT team.\(^9\) In each gtlike run, all point sources within the ROI and diffuse components in the model are fitted with the normalization left free. The spectral shapes are either fixed or set free depending on the specific analysis (see below). Note that we also include the 1FGL sources outside the ROI but within 14\(^\circ\) from S147 and their parameters are fixed at those of the 1FGL catalog. The count map of the ROI above 1 GeV (Figure 1, left) shows that the Crab Nebula and SNR IC443 are the dominant gamma-ray sources in this region. We model the Crab spectrum using three components (the Crab pulsar, the Crab PWN synchrotron, and the Crab PWN inverse Compton (IC) components) and fix their spectral shapes in the fit, following the previous LAT study (Abdo et al. 2010e). For SNR IC443, we model the emission as a broken power law (BPL) following Abdo et al. (2010b) and also fix its spectral shape.

3.1. Spatial Distribution

In Figure 1, we show a smoothed count map of the ROI above 1 GeV, a corresponding background model map, and the background-subtracted count map. The background model map includes contributions from the Galactic diffuse emission, the isotropic diffuse background, and nearby discrete sources. The model parameters of the diffuse components and nearby sources are set at the best-fit values obtained by gtlike using the data above 1 GeV. An extended gamma-ray source associated with S147 is visible in the background-subtracted map. In the model, the spatial distribution of the S147 source is assumed to be the H\alpha image (Finkbeiner 2003; see below). The spectral shape is fitted as a power-law function with the index set free. The point source in the inset is simulated with the same spectral shape as S147 obtained by the maximum likelihood fit.

We generated a test statistic (TS) map using the LAT data above 1 GeV in the S147 region (Figure 2, left). The TS is defined as \(-2\Delta \ln(\text{likelihood})\) and is obtained by gtlike between the models of the null hypothesis and an alternative. In this paper, we refer to the TS as a comparison between the models without a target source (null hypothesis) and with the source (alternative hypothesis) unless otherwise mentioned.

\(^9\) Available at the Fermi Science Support Center. http://fermi.gsfc.nasa.gov/ssc/

\(^10\) The flux of S147 would change <10% below 1 GeV and <4% above 1 GeV when we used the 2FGL catalog (Nolan et al. 2012).
In this map, the TS value at each grid position is calculated by using a model with a point source placed at the position, which has a power-law energy distribution with its index being free. The excess gamma rays above the backgrounds are distributed inside the SNR boundary, and the spatial extent is consistent with the remnant size. To evaluate the spatial extent, we fit the LAT PSF as shown in Figure 3. The gamma-ray map used for this comparison is the background-subtracted count map where all the model components except for the S147 source are subtracted as described above. Since the PSF depends on energy, we calculate the PSF by assuming the spectral index of the S147 source is 2.5, the best-fit value obtained with the Hα image convolved with the LAT PSF as shown in Figure 3. The gamma-ray map used for this comparison is the background-subtracted count map with a low number of photon counts. Note that the count map is not smoothed for the comparison of each region.

In Figure 3 and compare the gamma-ray (\(>1\) GeV) and Hα fluxes in each cell. We note that the size of the cell (\(~1^\circ\) ) is comparable with the LAT angular resolution (better than \(~1^\circ\) above 1 GeV). To take into account the LAT PSF for the morphological comparison, the Hα image is convolved with the LAT PSF as shown in Figure 3. The gamma-ray map used for this comparison is the background-subtracted count map where all the model components except for the S147 source are convoluted with a Gaussian kernel of \(\sigma = 0.25\) to show the clear spatial distribution of the S147 source with the low number of photon counts.

Figure 4 shows the resulting correlation diagram. The plotted gamma-ray counts are obtained by summing up the subtracted count map of the LAT in each region, and the Hα counts are calculated by summing up the Hα image convolved with the LAT PSF. The figure shows a possible correlation between the gamma-ray and Hα fluxes. Although it is challenging to establish the presence of the correlation given the large statistical uncertainty in the measurements, the observed correlation may provide insights into the physical processes that drive the emission.
uncertainties, the diagram suggests that an extension of the Fermi mission (~10 yr) will provide an opportunity to confirm it.

We also test different spatial templates, a disk template, sphere template, and a shell template, as shown in Figure 5. The disk template is a disk with a uniform surface brightness. The sphere template is a two-dimensional projection of a sphere with a uniform emissivity per unit volume. The shell is a two-dimensional projection of a spherical shell with a ratio of an inner diameter to outer diameter set to 0.8 based on the Hα map. The center positions and diameters of the disk, sphere, and shell templates are fitted to the data. By using the different templates, we perform maximum likelihood fits and compare the best-fit parameters in the energy range of 1–200 GeV. The spectral shape of the S147 source in the wide energy range is assumed to be a power-law function. As shown in Table 1, the S147 source is significantly detected in each case, and the obtained fluxes and spectral shapes are almost the same. The Hα image has the largest TS among all templates, despite the fact that the other templates have three additional free parameters (position and diameter) than those of the Hα image.

Given the results of the correlation diagram and the fits of the different spatial templates, the gamma-ray emission from the S147 source has a possible spatial correlation with the Hα filaments. Hereafter, we adopt the Hα image as the spatial template of the S147 source.

3.2. Spectrum

The spectral energy distribution (SED) of the source associated with S147 is obtained by dividing the 0.2–200 GeV energy band into six energy bins. Since each energy range for the fit is small, we model the Crab as a point source with a single spectral component instead of three. To model the bright emissions from Crab and IC443 in the small energy range, these spectral shapes are adopted to be power-law functions with free indices. The indices of the other sources are fixed at the values in the 1FGL catalog. S147 is fitted with a simple power-law function in each

![Diagram](image)

Figure 5. S147 source templates for the LAT spectral analysis. The templates are (a) a disk template, (b) a sphere template, (c) a shell template, and (d) an Hα image, overlaid with the contours of the LAT background-subtracted count map above 1 GeV (the same contours as those overlaid in Figure 2).

(A color version of this figure is available in the online journal.)
energy bin with its photon index fixed at 2.1, which is obtained by a broadband fitting in 0.2–200 GeV (see below). We note that the flux obtained for S147 in each energy bin is insensitive to the choice of index if it is confined to a reasonable range (say, 1–3). In each fit, all the sources within the ROI and the diffuse components in the model are fitted with their normalization free.

The systematic errors in the spectral analysis are mainly due to uncertainties associated with the underlying Galactic diffuse emission and the uncertainties of the effective area of the LAT. The uncertainties of the Galactic diffuse emission are primarily due to the imperfection of the Galactic diffuse model, the contributions from discrete sources not resolved from background, or both. We evaluate the uncertainties of the Galactic diffuse emission by measuring the dispersion of the fractional residuals in 10 regions around S147, which is where the Galactic diffuse component dominates (Figure 1). The fractional residuals, namely, (observed-model)/model, are calculated in three energy bands (0.20–0.45 GeV, 0.45–1.0 GeV, and 1.0–10 GeV) for each region. At each energy range, the uncertainties of the Galactic diffuse model are separately adopted as the second largest values among the 10 residuals (90% containment). From the results, the uncertainties are evaluated as 5.3%, 6.4%, and 8.9% at energy ranges of 0.20–0.45 GeV, 0.45–1.0 GeV, and 1.0–10 GeV, respectively. Systematic uncertainties of the effective area are 10% at 100 MeV, decreasing to 5% at 560 MeV, and increasing to 20% at 10 GeV and above (Rand et al. 2009). Note that the systematic errors associated with the choice of spatial models of S147 are negligible, since the best-fit parameters obtained by gtlike using the different spatial templates for S147 are almost the same as described in Section 3.1.

Figure 6 shows the resulting SED for S147. Total systematic errors are set by adding in quadrature the uncertainties due to the Galactic diffuse model and the effective area. Note that, given the conservative systematic errors, the upper limits are calculated for the spectrum of S147 below 1 GeV. Inspection of the figure indicates a steepening of the spectrum above a few GeV. To evaluate the significance of the steepening, we performed likelihood-ratio tests between a power-law function (the null hypothesis) and either an exponentially cutoff power-law or a smoothly BPL function (the alternative hypotheses) for the 0.2–200 GeV data. The exponentially cutoff power-law function is described as

\[
d\frac{N}{dE} = N_0 \left( \frac{E}{E_0} \right)^{-\Gamma} \exp \left( -\frac{E}{E_{\text{cut}}} \right),
\]

where \( E_0 \) is 1 GeV. The photon index \( \Gamma \), a cutoff energy \( E_{\text{cut}} \), and a normalization factor \( N_0 \) are free parameters. The resulting TS are \( TS_{\text{cutoff}} = -2 \ln(L_{\text{PL}}/L_{\text{cutoff}}) = 2.4 \) and \( TS_{\text{BPL}} = -2 \ln(L_{\text{PL}}/L_{\text{BPL}}) = 6.8 \), which correspond to significances of 1.5\( \sigma \) and 2.1\( \sigma \), respectively. There is an indication of the spectral steepening above a few GeV, but the possibility of a simple power-law spectrum cannot be conclusively rejected. The parameters obtained with the BPL model are photon indices \( \Gamma_1 = 1.4 \pm 0.5 \), \( \Gamma_2 = 2.5 \pm 0.15 \), and \( E_{\text{break}} = 1.0 \pm 0.8 \) GeV, with an integrated flux in 0.2–200 GeV of \( (3.8 \pm 0.6) \times 10^{-8} \) photon cm\(^{-2}\) s\(^{-1}\). The photon index obtained with the simple power law is 2.14 \( \pm 0.05 \). Using the result of the BPL, the gamma-ray luminosity in 0.2–200 GeV is calculated as \( 1.3 \times 10^{34} (d/1.3 \text{ kpc})^2 \text{ erg s}^{-1} \). The best-fit functions are represented in Figure 6.

### Table 1
Best-fit Values of Different Templates for the S147 Source

| Template | Center Position \((\alpha, \delta)\) | Diameter | Flux \((10^{-9} \text{ photons cm}^{-2} \text{ s}^{-1})\) | Photon Index | TS |
|----------|-----------------------------------|----------|---------------------------------|--------------|----|
| Disk     | (84:97, 27:97)                    | 3:5      | 9.2 \pm 1.1                     | 2.45 \pm 0.14| 86.6|
| Sphere   | (85:00, 27:93)                    | 3:9      | 9.2 \pm 1.1                     | 2.45 \pm 0.14| 84.7|
| Shell    | (85:29, 27:80)                    | 3:1      | 8.6 \pm 1.0                     | 2.51 \pm 0.15| 88.0|
| Her image| –                                 | –        | 8.5 \pm 1.0                     | 2.48 \pm 0.14| 94.8|

Note. The flux of the S147 source is calculated in the energy range of 1–200 GeV.

### Figure 6
SED of S147 measured by the Fermi LAT. The arrows represent the upper limit on the fluxes at a 90% confidence level. The total systematic errors are indicated by the black error bars, while the statistical errors \((1\sigma)\) are indicated by the red error bars. The black points and arrows represent the upper limits and take the systematic errors into consideration. The blue dashed, dotted, and solid lines represent the best-fit power-law, the exponentially cutoff power-law, and the smoothly BPL functions, respectively, from a binned likelihood fit in 0.2–200 GeV.

(A color version of this figure is available in the online journal.)
4. DISCUSSION

4.1. Modeling of Multiwavelength Spectra

Using 31 months of data acquired with the *Fermi* LAT, we found that extended GeV gamma-ray emission spatially coincides with S147. The size of the gamma-ray-emitting region is consistent with the shell of the Hα and radio emissions (∼200′). Moreover, the gamma-ray emission exhibits a possible correlation with the Hα filaments; therefore, also given the tight correlation between the Hα and radio maps (Xiao et al. 2008), there is also a possible correlation with the synchrotron radio filaments. We did not find a gamma-ray source at the position of PSR J0538 + 2817, which is considered to be the stellar remnant of the supernova explosion.

Let us consider the gamma-ray emissions from radio-emitting regions, which can be decomposed into filaments and diffuse regions (Xiao et al. 2008). The diffuse and filamentary components explain the radio data below and above a break around 1.5 GHz (∼10^−4 eV), respectively. The diffuse radio emission is supposed to come from the shocked gas behind the blast wave that is propagating in the intercloud medium (ICM), while the filaments are formed through the radiative shocks driven in the atomic clouds. We calculate the gamma-ray spectrum of each zone that is expected from the radio spectra under some reasonable assumptions. These components are only separated in the spectral space at the gamma-ray energies; this is because it is difficult to spatially resolve these components with the PSF of the LAT. The distance to the remnant is assumed to be \(d = 1.3 \text{ kpc}\), which is the most likely distance to the pulsar PSR J0538 + 2817 that is supposed to be associated with S147 (Ng et al. 2007; Chatterjee et al. 2009; Kramer et al. 2003). Following this assumption, the radius of the remnant is 38 pc. We also adopt a remnant age of \(t_0 = 3 \times 10^4\) yr from the kinematic age of PSR J0538 + 2817. The distance, radius, and age have uncertainties of 20%–30% (as described in Section 1).

After the supernova explosions, when the swept-up gas becomes comparable with the ejecta mass and the blast wave slows, the SNRs enter the Sedov–Taylor (adiabatic) phase (e.g., Truelove & McKee 1999). The total energy of the SNRs remains almost constant during the Sedov–Taylor phase because thermal and synchrotron radiation energy losses are negligible compared with the internal energy. The radiative phase begins when the radiative cooling dominates the energy loss of the SNRs and the adiabatic approximation breaks down. The transition time and radius to the radiative phase are

\[
\begin{align*}
t_r &= 1.3 \times 10^4 E_{51}^{3/14} n_{\text{ICM}}^{-4/7} \text{ yr}, \\
R_r &= 14 \times E_{51}^{2/7} n_{\text{ICM}}^{-3/7} \text{ pc},
\end{align*}
\]

where \(E_{51}\) is the explosion kinetic energy in units of \(10^{51}\) erg and \(n_{\text{ICM}}\) is the density of the intercloud gas in units of \(\text{cm}^{-3}\) (Cioffi et al. 1988). If S147 is in the Sedov phase, the density of the intercloud gas should be

\[
n_{\text{ICM}} = 0.24 E_{51}^{2/3} n_{\text{e}}^{-7/4}\text{cm}^{-3}\]

(\(\equiv n_{\text{e}}\)), which is derived from the condition of \(t < t_r\), where \(t_{30\text{kyr}} = t_0/(3 \times 10^4\) yr\). This result is consistent with the density of the intercloud gas calculated by the relation in the Sedov–Taylor stage:

\[
n_{\text{ICM}} = 3.3 \times 10^{-2} E_{51}^{2/3} R_{38\text{pc}}^{-5} \text{cm}^{-3},
\]

where \(R_{38\text{pc}} = R/(38\text{ pc})\). Alternatively, if we assume that S147 is in the radiative phase, the density of the intercloud gas should be \(n_{\text{ICM}} > n_{\text{e}}\). This leads to a smaller remnant that is incompatible with our preferred distance of 1.3 kpc. In this paper, we assume that S147 is in the Sedov phase.

The temporal evolution of the particle (protons/electrons) momentum distribution in the diffuse and filamentary zones can be described by

\[
\frac{\partial N_{e,p}^{d,f}}{\partial t} = \frac{\partial}{\partial p} (b_{e,p} N_{e,p}^{d,f}) + Q_{e,p}^{d,f},
\]

where \(b_{e,p} = -dp/dt\) is the momentum loss rate and \(Q_{e,p}^{d,f}(p)\) is the particle injection rate. The superscripts “d” and “f” of the parameters represent the diffuse and filamentary regions, respectively. To reproduce the spectral steepening in the radio band, we adopt the phenomenological forms for the injection distributions of the protons and electrons:

\[
Q_{e,p}^{d,f}(p) = a_{e,p}^{d,f} \left( \frac{p}{p_0} \right)^{-s} \exp \left( -\left( \frac{p}{p_{\text{cut},e,p}} \right)^2 \right),
\]

where \(p_0 = 1 \text{ GeV c}^{-1}\) and \(p_{\text{cut},e,p}\) is a cutoff momentum. Here, for simplicity, we assume that the injection rate is time independent. To obtain the radiation spectra from the remnant, \(N_{e,p}^{d,f}(p, t)\) is numerically calculated using parameters given in Table 2. We use \(N_0^{d,f}(p, t_0)\) and \(N_0^{d,f}(p, t_0/2)\) to calculate the radiative spectra from the diffuse region and filaments, respectively. The momentum losses for the electrons include synchrotron radiation, bremsstrahlung, IC scattering, and coulomb collisions, while the losses for the protons include pion production losses and coulomb collisions (Sturmer et al. 1997). In the case of the diffuse region, the adiabatic loss is also taken into account by using the Sedov–Taylor evolution. The gamma-ray emission mechanisms include the \(\pi^0\)-decay gamma rays due to high-energy protons and the bremsstrahlung and IC scattering processes by high-energy electrons. Calculations of the gamma-ray emission are performed by using the method described in Abdo et al. (2009). The interstellar field used for the IC calculations includes an infrared blackbody component (\(kT_{\text{IR}} = 3 \times 10^{-3} \text{ eV}, U_{\text{IR}} = 1 \text{ eV cm}^{-3}\)), an optical blackbody component (\(kT_{\text{opt}} = 0.25\text{ eV}, U_{\text{opt}} = 1 \text{ eV cm}^{-3}\)), and the cosmic microwave background. The infrared and optical components are set to reproduce the interstellar radiation field in the GALPROP code (Porter et al. 2008).

The physical parameters used for the model calculations are summarized in Table 2. The blast wave velocity is determined by \(v_b = 0.4R/t_0\) (e.g., Truelove & McKee 1999). The density of the intercloud gas \(n_{\text{ICM}}\) is determined by using Equation (5). Then, the postshock density in the diffuse region is set by \(n_{\text{sh}} = 4n_{\text{ICM}}\). When predicting the gamma-ray spectra, the magnetic field in the intercloud region is varied within the typical values of
1–5 μG. The compressed magnetic field in the diffuse region \( B_d \) is determined as \( B_d = \sqrt{2/3} (n_{Hd}/n_{ICM}) B_{ICM} \).

We assume that the filaments are formed by a radiative shock wave (50 km s\(^{-1} \) < \( v_f < 200 \) km s\(^{-1} \)) driven into the atomic clouds, which are denser than the ICM. The postshock gas is subject to radiative cooling, thus forming compressed gas (i.e., filaments). The gas density \( n_H \) and the temperature \( T_f \) of the filaments are estimated from the optical lines (Kirshner & Arnold 1979; Fesen et al. 1985; see Table 2). We adopt \( v_f = 100 \) km s\(^{-1} \) according to the optical observations (Lozinskaya 1976; Kirshner & Arnold 1979; Phillips et al. 1981). The density of the atomic clouds \( n_{ac} \) is calculated as

\[
\begin{align*}
n_{ac} &= n_{ICM} \left( \frac{v_f}{v_s} \right)^2 F, \\
\text{where}
\end{align*}
\]

\[
\begin{align*}
F &= 0.83 \times 10^7 \mu \text{G} \text{ cm}^{-3},
\end{align*}
\]

where \( v_s = v_f/(100 \) km s\(^{-1} \)) and \( F \simeq 3.2–4.8(v_f/v_b) + 2.6(v_f/v_b)^2 \) (McKee & Cowie 1975). The magnetic field strength in the filaments, \( B_f \), can be estimated from the pressure balance (Hollenbach & McKee 1979). The shock ram pressure \( P_{ram} = n_{ac} \mu \text{H} v_f^2 \) should be balanced by magnetic or thermal pressure, where \( n_{ac} \) is the gas density of the atomic clouds (preshocked gas of the filaments) and \( \mu \text{H} \) is the mass per hydrogen nucleus. When the magnetic pressure supports the filaments, the magnetic field strength is set by \( B_{ram} = B_f \sqrt{8/\pi} \). Using the relation of \( B_f = \sqrt{2/3} (n_{Hf}/n_{ac}) B_{ac} \),

\[
B_f \simeq 17 \times v_f^2 B_{ac}^{-1/3} n_{Hf}^{1/3} \mu \text{G},
\]

where \( B_{ac} = B_{ac}/(1 \) μG). The magnetic field in the atomic clouds \( B_{ac} \) is set in a range that is a few times higher than the typical intercloud magnetic field. When the thermal pressure supports the filaments, \( P_{ram} \) should be equated with the thermal pressure \( x_t n_{Hf} k T_f \), where \( x_t = 2.3 \), assuming that the filament gas is fully ionized, and \( k \) is the Boltzmann constant. In this case,

\[
B_f \simeq 60 \times v_f^2 B_{ac}^{-1/3} T_f^{-1} \mu \text{G},
\]

where \( T_f \) is \( T_f/(10^4) \text{K} \). The lower value between Equations (10) and (11) determines \( B_f \), which is found to be \( B_f \sim 100–300 \) μG for the adopted parameters.

We adjust the injection spectrum of electrons \( Q_x^{f,a}(p) \) (Equation (7)) to reproduce the observed radio spectrum, which is arguably the synchrotron radiation of the relativistic electrons. The free parameters of \( Q_x^{f,a}(p) \) are \( a_f^d, f^d, s \). We find that only the injection spectrum of electrons to protons, \( K_{ep} \equiv a_p/a_e \), is 0.01 to 1. A value of \( K_{ep} \) = 0.01 is similar to what is locally observed for CRs at GeV energies (e.g., Beisch et al. 2009).

The corresponding gamma-ray spectra are predicted using physical parameters varied within a range described in Table 2. The gamma rays are dominated by the \( 2\pi^-\)-decay emission for \( K_{ep} = 0.01 \). Figure 7 shows that the observed gamma-ray spectrum can be reproduced by using the parameters that are outlined above. The color-filled regions in the gamma-ray band represent the ranges of possible fluxes with variable physical parameters as described in Table 3. For case (a3), where the variable parameters are set at nearly central values in the expected ranges, the total kinetic energies of protons (\( W_p \)) are calculated as \( 1.7 \times 10^{47} \text{erg} \) and \( 10^{49} \text{erg} \) for the filaments and diffuse components, respectively. Although the \( W_p \) of the filaments is much smaller than that of the diffuse components, the observed gamma rays are dominated by the \( \pi^-\)-decay emission from the filaments due to the high density. The strong magnetic field of 210 μG also enhances the radio synchrotron emission from the filaments. Note that only the filament component can reproduce the observed gamma-ray spectral shape in any case.

In the case of \( K_{ep} = 1 \) (Table 4), the gamma-ray emission of the filaments is dominated by the electron bremsstrahlung, while that of the diffuse region has significant contributions of both the bremsstrahlung and IC scattering. Figure 8 shows that the observed gamma-ray spectrum is underpredicted for \( n_{Hf} = 100 \) cm\(^{-3} \). To reproduce the observed spectrum, \( n_{Hf} \gtrsim 500 \) cm\(^{-3} \) is preferable. However, the total kinetic energy of the relativistic protons is only \( W_p = 2.5 \times 10^{48} \text{erg} \) in case (b3). This value is only one-third of the energy content of the Galactic CR protons in the volume of SI47, \( W_{CR} = U_{CR} V \simeq 7.5 \times 10^{48} \text{erg} \), where \( U_{CR} \simeq 7.5 \text{eV cm}^{-3} \) is the energy density of CR protons and \( V = (4\pi R^3/3) \) is the volume of the SNR with a radius of \( R = 38 \) pc. This suggests that \( K_{ep} \) is unlikely to be 1.

\[
\begin{align*}
\text{4.2. Reacceleration of Galactic Cosmic Rays as Sources of \\
Gamma-ray-emitting Particles}
\end{align*}
\]

The total energy of the relativistic electrons obtained for the most reasonable set of parameters (i.e., case (a3)) is \( W_e \simeq 9 \times 10^{47} \text{erg} \) (see Table 3). This value is only three times higher than the total energy of the Galactic CR electrons stored in the ICM that SNR SI47 has swept up. This indicates

---

**Table 2**

| Basic Parameters of Multiwavelength Models |
|------------------------------------------|
| **SNR Dynamics** |
| Assumed parameters |
| Distance: \( d \) | 1.3 kpc |
| Age: \( t_f \) | 3 \times 10^6 \text{yr} |
| Explosion energy: \( E_{sn} \) | \((1-3) \times 10^{11} \) \text{erg} |
| Dependent parameters |
| Radius: \( R \) | 38 pc |
| Blast wave velocity: \( v_b \) | 500 km s\(^{-1} \) |

| Filament gas properties |
| Assumed parameters |
| Preshock magnetic field: \( B_{ac} \) | 3–10 μG |
| Gas density: \( n_{Hf} \) | 100–500 cm\(^{-3} \) |
| Temperature: \( T_f \) | 2 \times 10^6 \text{K} |
| Shock velocity: \( v_f \) | 100 km s\(^{-1} \) |
| Magnetic field: \( B_f \) | \( B_f(n_{Hf}, T_f, B_{ac}, v_f) \) |
| Preshock gas density: \( n_{ac} \) | 2–6 cm\(^{-3} \) |

| Diffuse gas properties |
| Assumed parameters |
| Preshock magnetic field: \( B_{ICM} \) | 1–5 μG |
| Magnetic field: \( B_d \) | 3–16 μG |
| Preshock gas density: \( n_{ICM} \) | 0.03–0.1 \text{cm}^{-3} |
| Gas density: \( n_{Hd} \) | 0.1–0.4 \text{cm}^{-3} |

### Note

* See Section 4.1.
the possibility that the observed spectra can only be explained by the emission from pre-existing CRs that were accelerated at the shock wave of the SNR shell. In Section 4.1, we modeled the radio and gamma-ray spectra without specifying the sources of the energetic particles. In this section, we calculate the emission from the relativistic particles produced by the acceleration...
(i.e., reacceleration) of the pre-existing CRs, following the prescription given by Uchiyama et al. (2010). The emission from two regions, i.e., the filament and diffuse, are considered in the same way as in Section 4.1.

The spectral distributions of the reaccelerated CRs are calculated as follows. The number density of the ambient CR protons and electrons, the seeds of reacceleration, are adopted as the spectra of the observed Galactic CR protons \(n_{\text{GCR, p}}(p)\) and electrons + positrons \(n_{\text{GCR, e}}(p)\):

\[
n_{\text{GCR, p}}(p) = 4\pi J_p p^{1.5} p_0^{-2.76},
\]

\[
n_{\text{GCR, e}}(p) = 4\pi J_e p^{1.5} p_0^{-2} (1 + p_0^2)^{-0.55},
\]

where \(p_0 = p/(\text{GeV e}^{-1})\), \(J_p = 1.9 \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}\), and \(J_e = 2 \times 10^{-2} \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}\) (Shikaze et al. 2007; Strong et al. 2004). We assume that the spectral distributions of the pre-existing relativistic particles in the atomic clouds (i.e., the preshocked gas of the filaments) are also the same as those of the Galactic CRs. At the shock wave, the CRs described above are assumed to accelerate according to the theory of diffusive shock acceleration (DSA; Blandford & Eichler 1987). The number density of the reaccelerated CRs as a function of momentum \(n_{\text{acc}}(p)\) is described as

\[
n_{\text{acc}}(p) = n_{\text{DSA}}(p) \times \exp\left(-\frac{p}{p_{\text{acc}}}ight)^2. \tag{15}
\]

Since the diffuse region is behind the shock wave, the number density of the relativistic particles in the diffuse region \(n_{\text{acc}}^d(p)\) has the spectral distribution from Equation (15). By contrast, the filaments are formed as the shocked gas is radiatively compressed. In this process, the particles frozen in the gas are heated and gain energy as \(p \rightarrow s^{1/3} p\), where \(s = (n_{\text{Hf}} N_{\text{acc}})/r_{\text{sh}}\), and the density increases by a factor of \(s\) (Blandford & Cowie 1982). Therefore, the number density of the accelerated and compressed particles in the filaments is calculated as \(n_{\text{acc}}^f(p) = s^{2/3} n_{\text{acc}}(s^{-1/3} p)\).

To calculate the multiwavelength spectrum, the same procedure and parameters used in Section 4.1 are applied here, except for the injection rates of the relativistic particles:

\[
Q_{\text{e, f}}(p) = (1 - f) V n_{\text{ICM}} n_{\text{Hd}} \times n_{\text{acc}}^f(p)/t_{\text{int}}^f, \tag{16}
\]

\[
Q_{\text{e, p}}(p) = f V n_{\text{acc}} n_{\text{Hd}} \times n_{\text{acc}}^f(p)/t_{\text{int}}^f, \tag{17}
\]

where \(t_{\text{int}}^d = t_0\) and \(t_{\text{int}}^f = t_0/2\) are the total injection times. The filling factor of the preshocked atomic gas is defined as \(f \equiv V_0/V\), where \(V_0\) and \(V\) are volumes of the atomic clouds and the SNR, respectively. In this scenario, the relativistic particle distributions are almost fixed, unlike those seen in Section 4.1. The free parameters of the particle distributions are only \(f\) and \(p_{\text{acc}}^d\). In the diffuse components calculation, the parameters \(B_d\) and \(p_{\text{acc}}^d\) are uniquely determined to fit the radio observational data. The gas density \(n_{\text{Hd}}\) which affects the calculated flux of the gamma-ray emission, ranges within the values listed in Table 2. We note that the gamma-ray emission in the diffuse region is negligible within this range of \(n_{\text{Hd}}\) compared with the emission in the filamentary region.
Alternatively, the gas properties of the filaments have the free parameters of \(n_{\text{Hf}}\) and \(n_{\text{dc}}\). When we set \(n_{\text{Hf}}\) and \(n_{\text{dc}}\) within the values listed in Table 2, the parameters \(B_f\), \(p_{\text{acc}}^f\), and \(f\) are uniquely determined to fit the observational data in the gamma-ray and radio bands.

Figure 9 shows the spectra in the case of \(n_{\text{Hf}} = 250\, \text{cm}^{-3}\), \(n_{\text{dc}} = 6\, \text{cm}^{-3}\), and \(n_{\text{Hd}} = 0.4\, \text{cm}^{-3}\). The cases of the different values of the parameters are summarized in Table 5. Note that the spectra are nearly the same for the values of the parameters in the table. The gamma-ray flux is dominated by the \(\pi^0\)-decay emission from the dense filaments due to the high densities of gas and CRs, as in the case of Section 4.1. This is consistent with the result given in Section 3.1, which indicates the spatial correlation between the GeV gamma-ray and the filamentary \(H\alpha\) emissions. The obtained magnetic pressures are consistent with the values listed in Table 2, except for the case of \(n_{\text{Hf}} = 100\, \text{cm}^{-3}\), where \(B_f = 70\, \mu\text{G}\) is slightly smaller than what is shown in the table.

In all cases, the filaments are supported by thermal pressure. While the intensity of the emission can be well explained, the observed spectral index is harder than the one calculated at a lower energy below the break in the radio band. This discrepancy could be attributable to a cutoff around 100 MHz (4 \times 10^{-7} \text{ eV}) due to the free–free absorption, which makes the spectral index harder than what is predicted by our model.

In this paper, we assume a compression ratio of 4 based on the specific heat ratio of the nonrelativistic gas (= 5/3). The compression ratio is expected to increase if we consider the effect of the relativistic gas whose specific heat ratio is 4/3. The precise treatment of this effect is beyond the scope of this paper. Here, let us consider the case of a compression ratio of 7 based on the specific heat ratio of the relativistic gas, i.e., the CRs. In this case, the calculated spectral index of the particle energy distribution becomes harder by \(\sim 0.5\). The reacceleration model can still explain the observed multiwavelength spectra when we set the values of \(f\) and \(B_d\) to \(\sim 60\%\) of those in the default case where the compression ratio is 4. The harder spectra explain the observed radio data better than the default case.

Middle-aged SNRs that interact with molecular clouds constitute the dominant class of SNRs detected by the Fermi LAT (see Uchiyama 2011). It has been proposed by Uchiyama et al. (2010) that the radiative filaments formed through these interactions between the molecular clouds and the SNR blast wave may account for the high gamma-ray luminosity of these SNRs (the Crushed Cloud model). In most cases, the reacceleration of the Galactic CRs is sufficient to supply the required CR density in the filaments. The scenario discussed in this section can be regarded as the atomic cloud version of the Crushed Cloud model, which is indeed insensitive to the physical parameters of a preshock cloud. The GeV gamma-ray emission from the Cygnus Loop (Katagiri et al. 2011) may also be explained by the Crushed Cloud model.

### 4.3. Dependence on the Distance

In Section 4.2, the distance to S147 is adopted as the distance to the plausibly associated pulsar. However, the absorption lines of the B1e star indicate a different distance. In this section, we consider a dependence on the distance for the reacceleration model as described in Section 4.2.

We first evaluate the dependence on the distance of the parameters in the diffuse region. The gas density in the diffuse region is estimated to be \(n_{\text{Hd}} = 4n_{\text{ICM}} \propto d^{-3}\) by using Equation (5). The total energy of the accelerated particles is \(E_{\text{acc}}^d \propto n_{\text{ICM}}^d (p) V \propto d^3\). Thus, the energy density \(U_{\text{acc}}^d = W_{\text{acc}}^d / V\)

\[
E^d_{\text{acc}} = \frac{W_{\text{acc}}^d}{V} \propto n_{\text{ICM}}^d (p) \propto d^3
\]
is independent of the distance. The emissivity of the synchrotron emission is proportional to $B^{(m+1)/2}$, assuming that the radiating electrons obey a power-law distribution with an index of $m$. Here, we approximate the distributions of the accelerated particles by a power-law distribution with an index of 1.8. The flux of the calculated synchrotron emission should explain the radio observational data for any distance: (the calculated flux) $\propto B_0^{(m+1)/2} W_p^2/d^2 \equiv \text{constant}$. Thus, the magnetic field $B_d$ is proportional to $-d^{-0.7}$. The photon energy of the synchrotron emission is approximately proportional to $\gamma^2 B$. To explain the observational break in the radio band, $\gamma \propto B_d^{-0.5} \propto d^{0.35}$. Next, we consider the parameters of the filaments. The filamentary gas density $n_{\text{H}}$ is derived from the optical observation, and it is independent of the distance. By contrast, the gas density of the atomic cloud is $n_{\text{acc}} \propto d^{-2.5}$ using Equation (8), where we use an approximate proportionality of $F \propto d^{0.5}$ around $d = 1.3$ kpc. The observed gamma-ray emission is reproduced by the $\pi^0$-decay emission in the filaments; (the calculated flux) $\propto n_{\text{H}} W_p^2/d^2 \equiv \text{constant}$, which leads the relation $W_p \propto d^2$. Since $W_p^2/d^2 \propto W_p/d^2$ is independent of the distance, the magnetic field $B_d$ should also be independent of the distance to reproduce the observed synchrotron emission in the radio band. Here, we define the compression ratio $r_{\text{comp}}$ as $n_{\text{H}}/n_{\text{acc}} \propto d^{2.5}$. The number distribution of the accelerated particles is dependent on the distance of $n_{e,p}^i(p) \propto s^{2/3} n_{\text{acc}}(s^{-1/3}/p) \propto \propto s^{2/3} (s^{-1/3}/p) \propto d^{3.2}$, where $s \equiv r_{\text{comp}}/r_{\text{sh}} \propto d^{2.5}$. Thus the energy density is estimated to be $U_p^i \propto n_{e,p}^i(p) \propto d^{3.2}$. The total energy is described as $W_p \propto f V / r_{\text{comp}} \propto n_{e,p}^i(p)$, which yields a filling factor of $f \propto d^{-1.7}$. The cutoff momentum $p_{\text{acc}}^\gamma$ is determined by the observed gamma-ray data. Since $p_{\text{acc}}^\gamma$ is approximately proportional to the gamma-ray cutoff calculated by the $\pi^0$-decay emission, the cutoff is dependent on the distance of $p_{\text{acc}}^\gamma \propto s^{-1/3} \propto d^{-0.8}$. Table 6 shows one of the parameter sets of the reacceleration model for the case of $d = 0.88$ kpc. The dependence on the distance $d$ is also summarized in the table. The observed intensity of the gamma-ray and the radio emission is also reproduced by the reacceleration model for $d = 0.88$ kpc. We note that the contribution of the gamma rays in the diffuse region is not negligible below a few GeV, when $n_{\text{H}}$ is greater than $\sim 2$ cm$^{-3}$. In any case, the gamma-ray emission of the filaments is needed to explain the observed data above a few GeV.

5. CONCLUSIONS

We have presented results for the GeV gamma-ray observations of the region around SNR S147 using about 31 months of data accumulated by the Fermi LAT. The gamma-ray emission is spatially extended and is consistent with the size of S147 ($\sim 200'$. There is no indication that the gamma-ray emission comes from the associated pulsar PSR J0538 + 2817. The best fit to the LAT data is obtained using the Hα image as an SNR spatial template rather than as simple geometrical shapes. The comparisons between the gamma-ray and Hα fluxes indicate a possible correlation between them, suggesting that the gamma rays come from the thin filaments observed in the Hα and radio bands. The observed energy spectrum between 0.2 and 200 GeV indicates spectral steepening; a smoothly BPL provides a better fit than a simple power law at a $\sigma$ significance, which means that the possibility of a simple power law cannot be rejected. The gamma-ray luminosity amounts to $1.3 \times 10^{34} (d/1.3 \text{ kpc})^2 \text{ erg s}^{-1}$.

The LAT spectrum is best explained by the $\pi^0$-decay gamma rays from the relativistic protons in the dense filaments. We find that the reacceleration of the pre-existing CRs and the subsequent adiabatic compression in the filaments are sufficient enough to provide the required energy density of the high-energy electrons and protons. There are two main distance estimates to S147: one from the pulsar association (1.3 kpc) or one from the absorption lines ($< 0.88$ kpc). We consider the cases of 1.3 kpc and 0.88 kpc, and the gamma-ray emission can be explained in the same framework for either distance. SNR S147 offers a firm example of the realization of the Crushed Cloud model and supports the importance of the dense filaments in the SNRs as gamma-ray production sites.

We thank the anonymous referee for suggestions that have improved this paper. The Fermi LAT Collaboration acknowledges the generous, ongoing support from a number of agencies and institutes that have supported both the development and the operation of the LAT as well as the scientific data analysis. These include the National Aeronautics and Space Administration, the U.S. Department of Energy, the Commissariat à l’Energie Atomique, the Centre National de la Recherche Scientifique/Institut National de Physique Nucléaire et de Physique des Particules, the Agenzia Spaziale Italiana, the Istituto Nazionale di Fisica Nucleare, the Ministry of Education, Culture, Sports, Science and Technology, the High Energy Accelerator Research Organization, the Japan Aerospace Exploration Agency, and the K. A. Wallenberg Foundation, the Swedish Research Council, and the Swedish National Space Board.

Additional support for our scientific analysis during the operations phase is gratefully acknowledged from the Istituto Nazionale di Astrofisica and the Centre National d’Études Spatiales.

REFERENCES
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, ApJ, 706, L1 (W51C)
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010a, Science, 327, 1103 (W44)
