The Astrophysical Journal Letters, 749:L35 (5pp), 2012 April 20 doi:10.1088/2041-8205/749/2/L35

FERMI LARGE AREA TELESCOPE DISCOVERY OF GeV GAMMA-RAY EMISSION FROM THE VICINITY OF SNR W44

Yasunobu Uchiyama[1,2,8], Stefan Funk[1,2], Hideaki Katagiri[3], Junichiro Katsuta[1], Marianne Lemoine-Goumard[4], Hiroyasu Tajima[2,5], Takaaki Tanaka[2], and Diego F. Torres[6,7]
[1] SLAC National Accelerator Laboratory, 2575 Sand Hill Road M/S 29, Menlo Park, CA 94025, USA; uchiyama@slac.stanford.edu
[2] Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94305, USA
[3] College of Science, Ibaraki University, 2-1-1, Bunkyo, Mito 310-8512, Japan
[4] Centre d'Études Nucléaires de Bordeaux Gradignan, Université Bordeaux 1, CNRS/IN2p3, 33175 Gradignan, France
[5] Solar–Terrestrial Environment Laboratory, Nagoya University, Nagoya 464-8601, Japan
[6] Institut de Ciències de l'Espai (IEEE-CSIC), Campus UAB, 08193 Barcelona, Spain
[7] Institució Catalana de Recerca i Estudis Avançats (ICREA), Barcelona, Spain
Received 2012 February 28; accepted 2012 March 14; published 2012 April 2

ABSTRACT

We report the detection of GeV γ-ray emission from the molecular cloud complex that surrounds the supernova remnant (SNR) W44 using the Large Area Telescope on board *Fermi*. While the previously reported γ-ray emission from SNR W44 is likely to arise from the dense radio-emitting filaments within the remnant, the γ-ray emission that appears to come from the surrounding molecular cloud complex can be ascribed to the cosmic rays (CRs) that have escaped from W44. The non-detection of synchrotron radio emission associated with the molecular cloud complex suggests the decay of π^0 mesons produced in hadronic collisions as the γ-ray emission mechanism. The total kinetic energy channeled into the escaping CRs is estimated to be $W_{\rm esc} \sim (0.3\text{–}3) \times 10^{50}$ erg, in broad agreement with the conjecture that SNRs are the main sources of Galactic CRs.

Key words: acceleration of particles – cosmic rays – ISM: supernova remnants – radiation mechanisms: non-thermal

Online-only material: color figures

1. INTRODUCTION

Diffusive shock acceleration (DSA) operating at expanding shock waves (e.g., Malkov & O'C Drury 2001) is widely accepted as the mechanism to convert the kinetic energy released by supernova explosions into the energy of relativistic protons and nuclei (or cosmic rays (CRs)) that obey a power-law type distribution. In DSA theory, CRs being accelerated at shocks must be scattered by self-generated magnetic turbulence. Since the highest-energy CRs upstream in the shock precursor are prone to lack self-generated turbulence, they are expected to escape from the shock. The character of escaping CRs reflects complex interplay between CRs and magnetic turbulence, which is yet to be understood. DSA theory generally predicts that a substantial fraction of the shock energy is carried away by escaping CRs, and therefore they should be treated as an integral part of the DSA process (Ellison & Bykov 2011).

Depending on the amount of nuclear CRs released by a supernova remnant (SNR) and the diffusion coefficient in the interstellar medium, the molecular clouds illuminated by escaping CRs in the vicinity of SNRs are expected to be luminous in γ-rays due to the enhanced π^0-decay γ-rays (Aharonian & Atoyan 1996; Rodriguez Marrero et al. 2008; Aharonian 2004; Gabici et al. 2009). The TeV γ-ray emission seen in the vicinity of SNR W28 (Aharonian et al. 2008b) can be regarded as a realization of this scenario.

Recent detections of intense GeV γ-ray emission from SNRs interacting with molecular clouds (e.g., Abdo et al. 2009, 2010a, 2010b, 2010c; Castro & Slane 2010; Giuliani et al. 2011) provide an interesting opportunity to study how CRs escape from SNRs and propagate in the interstellar medium. However, it has not been clear whether the γ-ray emission is produced by escaping CRs or by trapped CRs (Uchiyama 2011), since shocked molecular clouds inside an SNR also could be the sites of efficient γ-ray production (Bykov et al. 2000; Uchiyama et al. 2010).

In this Letter, we report the *Fermi* Large Area Telescope (LAT) observations of the region around SNR W44. We demonstrate that the γ-ray emission distributed on a spatial scale much larger than the remnant is attributable to a CR halo around SNR W44.

2. OBSERVATION AND ANALYSIS

LAT on board *Fermi* is a pair-conversion γ-ray detector that covers a very wide range of energy from 20 MeV to >300 GeV (Atwood et al. 2009). The LAT tracks the electron and positron resulting from pair conversion of an incident γ-ray in thin high-Z foils, and measures the energy deposition due to the subsequent electromagnetic shower that develops in the calorimeter. The point-spread function (PSF) varies with photon energy and improves at higher energies. The 68% containment radius is smaller than $0^\circ\!.5$ above $\sim$2 GeV.

We use the γ-ray data acquired from 2008 August 4 to 2011 September 6. The *Source* class events are analyzed using the instrument response functions `P7SOURCE_V6`. A cut on earth zenith angles greater than 100° is applied to reduce the residual γ-rays from cosmic-ray interactions in the upper atmosphere. We analyze photons with energy $\geqslant$2 GeV, where the PSF is sharp enough to disentangle multiple spatial components. In-depth analysis below 2 GeV will be published elsewhere.

Spectral and spatial parameter estimation is done by maximizing the likelihood of the source model (e.g., Mattox et al. 1996) using "binned" `gtlike` of the *Fermi* Science Tools. The region

[8] Panofsky Fellow.

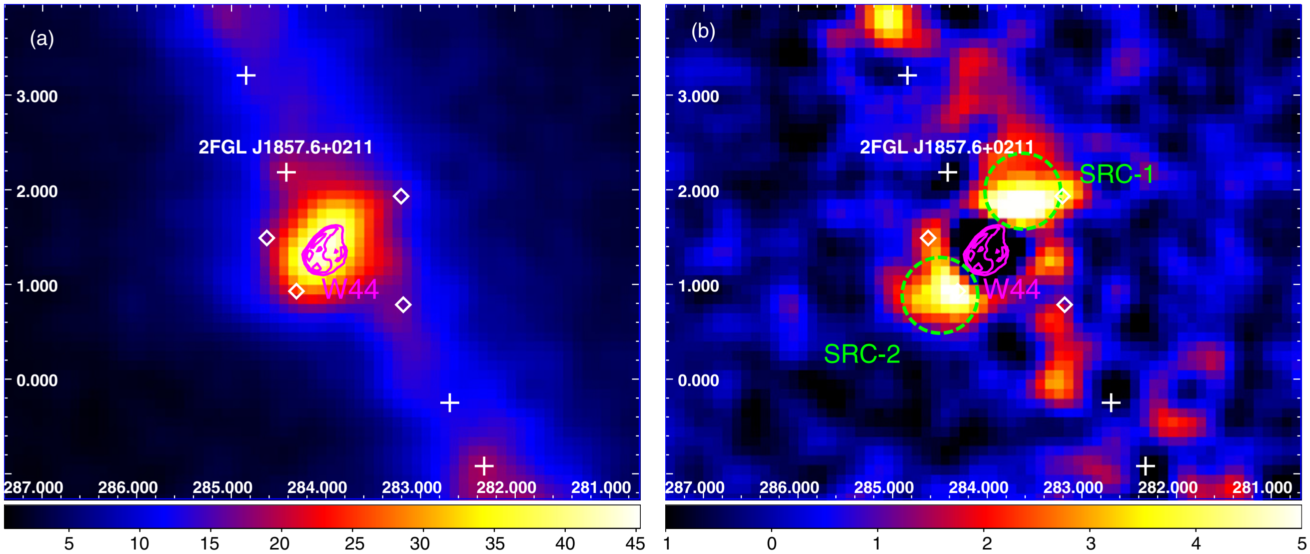

Figure 1. (a) *Fermi*-LAT γ-ray count map for 2–100 GeV around SNR W44 in units of counts per pixel ($0\overset{\circ}{.}1 \times 0\overset{\circ}{.}1$) in celestial coordinates (J2000). Gaussian smoothing with a kernel $\sigma = 0\overset{\circ}{.}3$ is applied to the count maps. Magenta contours represent a 10 GHz radio map of SNR W44 (Handa et al. 1987). 2FGL sources included in the maximum likelihood model are shown as crosses, while those removed from the model are indicated by diamonds. (b) The difference between the count map in (a) and the best-fit (maximum likelihood) model consisting of the Galactic diffuse emission, the isotropic model, 2FGL sources (crosses), and SNR W44 represented by the radio map. Excess γ-rays in the vicinity of W44 are referred to as SRC-1 and SRC-2.

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

used for the likelihood analysis is $10^\circ \times 10^\circ$, centered on W44. The γ-ray source model includes point sources listed in the second *Fermi*-LAT catalog (2FGL sources; Nolan et al. 2012), Galactic interstellar diffuse emission, and an isotropic component (extragalactic and residual particle background). The Galactic diffuse emission is modeled using the standard ring-hybrid model, `gal_2yearp7v6_v0.fits`, with its normalization being left free. We use a tabulated spectrum written in `iso_p7v6source.txt` as the isotropic diffuse emission. The LAT data, analysis software, and diffuse models are made publicly available through the *Fermi* Science Support Center.[9]

Figure 1(a) shows a 2–100 GeV count map in the vicinity of SNR W44, where crosses and diamonds indicate the positions of 2FGL sources. In addition to W44, five 2FGL sources are distributed within $1\overset{\circ}{.}5$ from W44. One of them, 2FGL J1857.6 + 0211, coincides with PSR B1855 + 02 and also with SNR G35.6−0.4[10] that has recently been re-identified as an SNR (Green 2009). The other nearby 2FGL sources (diamonds) do not have clear counterparts in other wavelengths, and they are excluded from the source model to investigate the surroundings of W44.

We employ a synchrotron radio map of SNR W44 taken from Handa et al. (1987) to model the spatial distribution of the γ-ray emission from W44, given that the synchrotron and γ-ray emission from W44 are expected to be co-spatial (see Section 4.1). The γ-ray spectrum is assumed to obey a power law.

3. RESULTS

The likelihood analysis is performed using the source model described above. For point sources, we use the spectral models adopted for each source in the 2FGL catalog analysis. Spectral normalizations of point sources located $<3^\circ$ from W44 are allowed to vary in the likelihood fit, while the spectral parameters of the other field sources are fixed using the 2FGL catalog. The normalization and photon index of W44 are left free; a photon index of $\Gamma_{\rm W44} = 2.94 \pm 0.07$ is obtained in agreement with our previous work (Abdo et al. 2010a). Figure 1(b) shows a residual count map, where the observed count map in 2–100 GeV is subtracted by the best-fit sky model. Significant excess γ-rays are seen in the vicinity of W44; the features are referred to here as SRC-1 and SRC-2. The statistical significance is found to be $\sim 9\sigma$ for SRC-1 and $\sim 10\sigma$ for SRC-2.

The residual count map depends weakly on the choice of the spatial template that describes γ-rays from W44. Our simulations using `gtobssim` verified that SRC-1 and SRC-2 are not caused by photons leaking from W44 due to the PSF of LAT. Also we checked the robustness of the results by selecting only the front-converted events.

We perform spectral analysis of SRC-1/2 by modeling each source as a disk with a $0\overset{\circ}{.}4$ radius (see Figure 1). The resulting γ-ray spectra are plotted in Figure 2 along with the spectrum obtained for SNR W44. Adding the SRC-1/2 disks to the source model does not significantly affect the W44 spectrum. The power-law photon index is found to be $\Gamma = 2.56 \pm 0.23_{\rm sta} \pm 0.2_{\rm sys}$ and $\Gamma = 2.85 \pm 0.23_{\rm sta} \pm 0.2_{\rm sys}$ for SRC-1 and SRC-2, respectively. The systematic errors are evaluated from different choices of the sky models describing W44 and SRC-1/2 and from the uncertainties of the effective area. The imperfection of the diffuse emission model and its possible impact on the results are discussed below. We tested a smoothly broken power law and exponentially cutoff power law for SRC-1/2 but found that the spectral fits do not significantly improve.

4. DISCUSSION

We have discovered GeV γ-ray sources on the periphery of SNR W44. It has long been known that a complex of giant

9 http://fermi.gsfc.nasa.gov/ssc/

10 PSR B1855 + 02 is located near the center of G35.6−0.4. At the southern border of G35.6−0.4, there is a TeV γ-ray source HESS J1858 + 020 (Aharonian et al. 2008a), toward which one or more molecular clouds have been found (Paron & Giacani 2010). Discussion of HESS J1858 + 020 can be found in Torres et al. (2011).

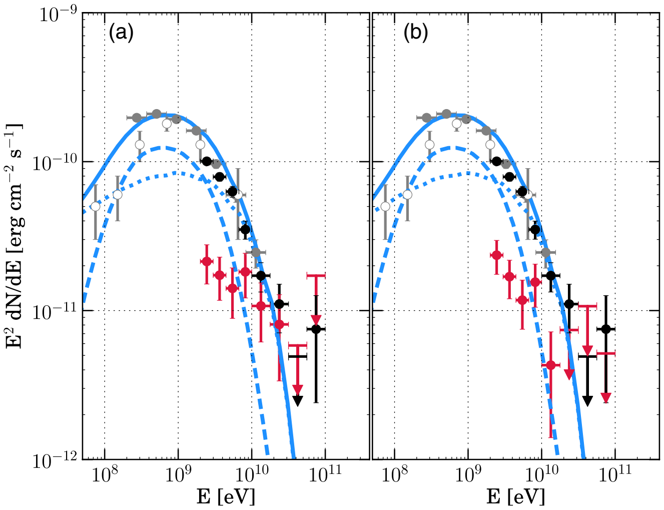

Figure 2. (a) *Fermi*-LAT spectrum of SRC-1 (red points) along with the LAT spectra of SNR W44 from this work (black points) and previous one (Abdo et al. 2010a, gray points). The γ-ray spectrum reported by AGILE is also shown (Giuliani et al. 2011, open circles). Systematic errors are added in quadrature to the errors of the SRC-1 spectrum. The model curves describe the emission from SNR W44 (see Section 4.1), consisting of π^0-decay γ-rays (dashed curves) and relativistic bremsstrahlung (dotted curves). (b) Same as (a) but the LAT spectrum of SRC-2 is shown instead of SRC-1.

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

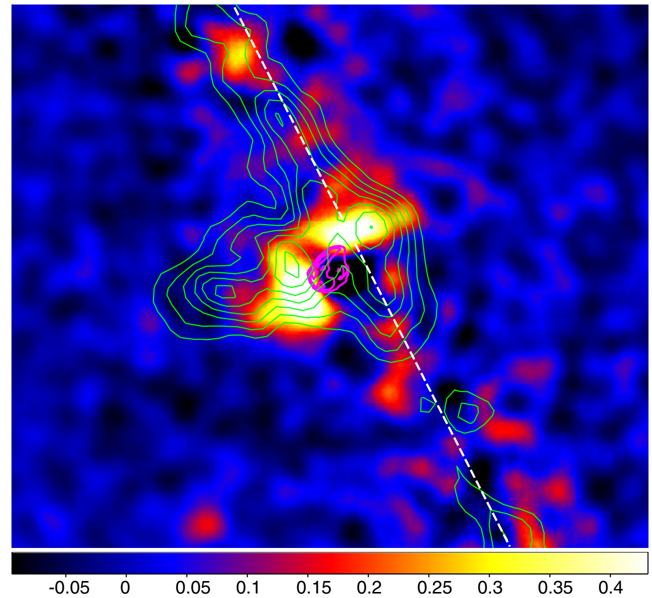

Figure 3. *Fermi*-LAT residual count map highlighting the γ-ray emission from the surroundings of SNR W44. Magenta contours present the synchrotron radio map of SNR W44. Green contours show CO ($J = 1 \rightarrow 0$) emission integrated over velocity from 30 to 65 km s^{-1} with respect to the local standard of rest (Dame et al. 2001), tracing the molecular cloud complex that surrounds SNR W44. The contours start from 20 K km s^{-1} with an interval of 10 K km s^{-1}. Some molecular clouds not associated with W44 are also seen along the Galactic plane (dashed line) in the CO map.

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

molecular clouds (GMCs) surrounds SNR W44; the spatial extent is as large as 100 pc and the total mass of the complex amounts to $\sim 1 \times 10^6\, M_\odot$ (Dame et al. 1986; Seta et al. 1998). In Figure 3, the γ-ray emission from the surroundings of W44 is compared with a CO ($J = 1 \rightarrow 0$) map (Dame et al. 2001) integrated over a velocity range of 30–65 km s^{-1} appropriate for the GMC complex. The regions of excess γ-rays overlap with the surrounding GMC complex.

The γ-ray emission in the vicinity of W44 can be ascribed formally to possible imperfection of the maps of gas column densities used in the model of the Galactic interstellar diffuse emission or to a local enhancement of CR density. The former implies that the mass in the γ-ray-emitting region around W44 is underestimated by a large factor ($\gtrsim 5$), or it requires the presence of unknown background clouds with a huge mass of $\gtrsim 10^6\, M_\odot$. Therefore, an overabundance of CRs in the vicinity of W44 offers a more sensible explanation; we present a model in which the GMC complex is illuminated by CRs that were produced in SNR W44 and escaped from it. We first model the γ-ray emission from W44 itself, and then proceed with modeling the γ-ray emission from the surroundings.

We adopt the following parameters to describe SNR W44 (Uchiyama et al. 2010 and references therein): (1) $d = 2.9$ kpc as the distance to W44 based on the firm association with the surrounding GMCs (e.g., Seta et al. 1998), (2) $R = 12.5$ pc as the radius (corresponding to the angular radius of $\theta = 14.8'$), (3) the kinetic energy released by the supernova $E_{\rm SN} = 2 \times 10^{51}$ erg, (4) the ejecta mass $M_{\rm ej} = 2\, M_\odot$, and (5) the remnant age[11] $t_{\rm age} = 10{,}000$ yr. Assuming evolution in the uniform intercloud medium, these parameters imply that the intercloud medium has hydrogen density of $n \simeq 2$ cm^{-3} and the Sedov–Taylor phase started around $t = t_{\rm ST} \simeq 129$ yr when the radius was $r_{\rm ST} \simeq 1.9$ pc.

4.1. *Gamma-Ray Production Inside SNR W44*

A high-resolution radio continuum map of SNR W44 is dominated by filamentary structures of synchrotron radiation (Castelletti et al. 2007). The radio emission is thought to arise from radiatively compressed gas behind fast dissociative shocks driven into molecular clouds that are engulfed by the blast wave (Reach et al. 2005). Assuming typical magnetic fields of molecular clouds, the GeV γ-ray flux relative to the radio flux is expected to be high enough to account for the γ-ray emission from SNR W44, irrespective of the origin of the high-energy particles (Uchiyama et al. 2010).

The dense radio-emitting filaments are indeed the most probable sites of the dominant γ-ray production in SNR W44, given the estimated mass of $M_{\rm sh} = 5 \times 10^3\, M_\odot$ (Reach et al. 2005), which is $\sim$9 times larger than the swept-up intercloud mass. Assuming a pre-shock cloud density of $n_0 = 200$ cm^{-3} (Reach et al. 2005) and a pre-shock magnetic field of $B_0 = 30\,\mu$G, we can estimate the compressed gas density and magnetic field in the filaments as $n_m \simeq 7 \times 10^3$ cm^{-3} and $B_m \simeq 0.8$ mG following the prescription in Uchiyama et al. (2010).

For simplicity we describe the energy distributions of CR electrons and protons in the filaments as a cutoff power law in momentum: $n_{e,p}(p) = k_{e,p}\, p^{-1.74} \exp(-p/p_{\rm c})$, where the index is chosen to match the radio spectral index of $\alpha \simeq 0.37$ (Castelletti et al. 2007). The ratio of radio and γ-ray fluxes yields $k_e/k_p = 0.05$. The spectral break in the LAT spectrum is reproduced by $p_{\rm c} = 10$ GeV c^{-1}. As shown in Figure 2, the spectrum below a few GeV is dominated by the decays of π^0-mesons produced in the dense filaments,[12] while the

[11] The SNR age is comparable to the spin-down age of the pulsar B1853 + 01 associated with SNR W44, $\tau_{\rm sd} = 20{,}000$ yr (Wolszczan et al. 1991).

[12] The AGILE spectral data (Giuliani et al. 2011) are not taken into account in the model. They will be discussed elsewhere in light of a low-energy spectrum measured with *Fermi*.

falling part of the LAT spectrum is contributed largely by the electron bremsstrahlung. The energy density of the CR protons amounts to $u_p \simeq 4 \times 10^2\ (M_{\rm sh}/5 \times 10^3\ M_\odot)^{-1}$ eV cm^{-3}, which could be explained by reacceleration of Galactic CRs (GCRs) preexisting in a molecular cloud (Uchiyama et al. 2010). However, we do not specify the dominant source of the γ-ray-emitting particles, since freshly accelerated CRs could also enter the filaments diffusively from the intercloud medium. Provided that u_p corresponds to the mean CR density in the shell of the remnant, the total kinetic energy of CRs is $W_p \simeq 0.4 \times 10^{50}\ (M_{\rm sh}/5 \times 10^3\ M_\odot)^{-1}$ erg.

4.2. *Gamma-Rays from the Surroundings of W44*

The CR distributions in the surroundings of SNR W44 should be determined by (1) how CRs are released into the ambient medium, and (2) the diffusion coefficient of the interstellar medium, $D_{\rm ISM}(p)$ (e.g., Gabici et al. 2009). We consider only CR protons since leptonic emissions are unimportant for an e–p ratio of $\sim$0.01. Also, the non-detection of synchrotron radio emission from the GMC complex indicates that electron bremsstrahlung is not the main γ-ray production mechanism.

Let us assume that CRs with a momentum p can escape from the surface of an SNR at time $t = t_{\rm esc}(p)$ when the SNR radius becomes $R_{\rm esc}(p)$, and that $t_{\rm esc}(p)$ has a power-law form:

$$t_{\rm esc}(p) = t_{\rm ST}\left(\frac{p}{p_{\rm max}}\right)^{-1/\chi}, \qquad (1)$$

where we adopt $p_{\rm max} = 10^{15}$ eV c^{-1} and $\chi = 3$, following Gabici et al. (2009) and Ohira et al. (2011). This implies that SNR W44 is currently releasing CRs with $p = p_0 \simeq 2$ GeV c^{-1}. A simple Sedov–Taylor evolution gives $R_{\rm esc}(p) = r_{\rm ST}(p/p_{\rm max})^{-2/5\chi}$.

The runaway CR spectrum integrated over SNR expansion is expected to be of the form $N_{\rm esc}(p) \propto p^{-2}$ (Ptuskin & Zirakashvili 2005). However, depending on the time history of acceleration efficiency and maximum energy, it could be different from p^{-2} (Ohira et al. 2010; Caprioli et al. 2010). We parameterize the total spectrum of CRs injected into the interstellar space as $N_{\rm esc}(p) = k_{\rm esc}\, p^{-s} \exp(-p/p_{\rm max})$.

The distribution function of the runaway CRs at time t at a distance r from the SNR center, $n(p, r, t)$, is described by a well-known diffusion equation, which can be solved using the method developed by Atoyan et al. (1995). We use the following solution of the diffusion equation (Ohira et al. 2011):

$$n(p, r, t) = \frac{N_{\rm esc}(p)}{4\pi^{3/2} R_d R_{\rm esc} r}\left[e^{-(r-R_{\rm esc})^2/R_d^2} - e^{-(r+R_{\rm esc})^2/R_d^2}\right], \qquad (2)$$

where

$$R_d(p, t) \equiv 2\sqrt{D_{\rm ISM}(p)[t - t_{\rm esc}(p)]}. \qquad (3)$$

The diffusion coefficient of the interstellar medium is often parameterized as

$$D_{\rm ISM}(p) = 10^{28}\ D_{28}\left(\frac{p}{10\ {\rm GeV}\ c^{-1}}\right)^{\delta}\ {\rm cm^2\ s^{-1}}, \qquad (4)$$

with constants of $D_{28} \sim 1$ and $\delta \sim 0.6$ based on the GCR propagation model (Ptuskin et al. 2006). The diffusion coefficient in the close vicinity of an SNR may be different from the Galactic average, for example, because of Alfvén waves generated by CRs themselves (Fujita et al. 2010). We allow D_{28} to vary, but fix the index to be $\delta = 0.6$ for simplicity.

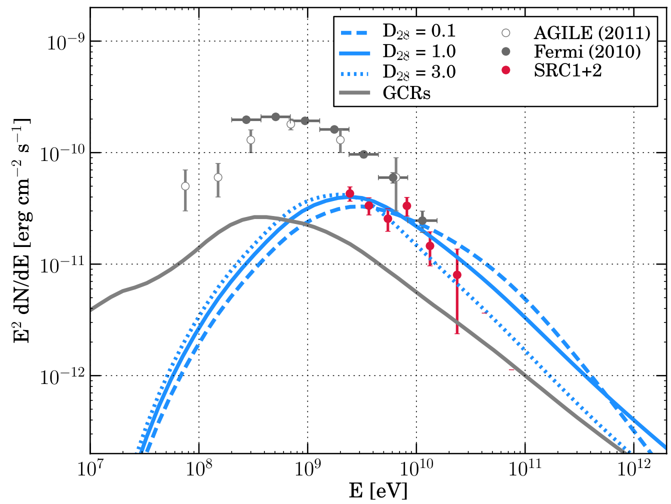

Figure 4. Modeling of the γ-ray emission from the molecular cloud complex that surrounds W44. Data points are from Figure 2, but SRC-1 and SRC-2 are co-added. The SRC-1+2 spectrum (red points with statistical errors) is attributable to the π^0-decay γ-rays from the cloud complex illuminated by the CRs that have escaped from W44 (blue curves). Three cases of diffuse coefficient, $D_{28} = 0.1, 1, 3$, are shown. A gray curve indicates the γ-ray spectrum produced by the sea of GCRs in the same CR-illuminated clouds.

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

Given that the γ-ray emission by the escaping CRs is visible against SNR W44 in the LAT image, we expect that the size of the CR halo, $R_{\rm CR}(p) = R_d(p, t_{\rm age}) + R_{\rm esc}(p)$, is much larger than the size of the remnant $R = 12.5$ pc. Since we find $R_{\rm CR}(100\ {\rm GeV}\ c^{-1}) \simeq 2R$ for $D_{28} = 0.1$, we set $D_{28} \geqslant 0.1$. Note however that the constraint depends on the exact choice of $t_{\rm age}$; $D_{28} \geqslant 0.05$ is obtained for $t_{\rm age} = 20{,}000$ yr.

To calculate the γ-ray emission from the surroundings of W44, we also need to specify the mass distribution. The total mass of the cloud complex illuminated by the runaway CRs is estimated as $M_{\rm MC} \sim 5 \times 10^5\ M_\odot$ by adding up six molecular clouds (Clouds 1–6) in Seta et al. (1998). The mass is assumed to be uniformly distributed within the radius of the molecular cloud complex, $R_{\rm MC} = 50$ pc. Given the spherical symmetry of the model, we combine the γ-ray spectra of SRC-1 and SRC-2.

Effectively, our model has three adjustable parameters, D_{28}, $k_{\rm esc} M_{\rm MC}$, and s. As shown in Figure 4, we determine $k_{\rm esc} M_{\rm MC}$ (i.e., the normalization) and s to reproduce the γ-ray spectrum for three values of the diffusion coefficient: $D_{28} = 0.1, 1, 3$. For slow diffusion of $D_{28} = 0.1$, a steep index of $s = 2.6$ is required since CR protons with $p \lesssim 400$ GeV c^{-1} are still within the GMC complex. CRs at higher energies are leaking from the complex, and correspondingly the γ-ray spectrum exhibits a break at $\sim$50 GeV. Though the steep injection index required for the slow diffusion case is not theoretically expected (Caprioli et al. 2010), this problem may be alleviated by adopting a larger value of δ. The total amount of CRs released into interstellar space amounts to $W_{\rm esc} \simeq 0.3 \times 10^{50}\ (M_{\rm MC}/5 \times 10^5\ M_\odot)^{-1}$ erg. For a nominal value of $D_{28} = 1$, we obtain $s = 2.0$ and $W_{\rm esc} \simeq 1.1 \times 10^{50}\ (M_{\rm MC}/5 \times 10^5\ M_\odot)^{-1}$ erg; the γ-ray spectrum in the LAT range is steepened due to energy-dependent escape from the GMC complex. Finally, we find $s = 2.0$ and $W_{\rm esc} \simeq 2.7 \times 10^{50}\ (M_{\rm MC}/5 \times 10^5\ M_\odot)^{-1}$ erg to reproduce the spectrum in the case of $D_{28} = 3$.

We estimate that the energy channeled into the escaping CRs amounts to $W_{\rm esc} \sim (0.3$–$3) \times 10^{50}$ erg. On the other hand, the CR content trapped in W44 is estimated roughly as $W_p \sim 0.4 \times 10^{50}$ erg assuming a uniform CR distribution between the SNR shell and radio filaments (Section 4.1). A combination of the *Fermi*-LAT data to be obtained with longer exposures, and future operation of the Cherenkov Telescope Array will put more stringent constraints on the models through the determination of γ-ray spatial distributions as a function of energy.

The *Fermi*-LAT Collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy and CNES in France for science analysis during the operation phase is also gratefully acknowledged.

REFERENCES

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, ApJ, 706, L1
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010a, Science, 327, 1103
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010b, ApJ, 712, 459
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010c, ApJ, 718, 348
Aharonian, F. A. 2004, Very High Energy Cosmic Gamma Radiation: a Crucial Window on the Extreme Universe (Singapore: World Scientific)
Aharonian, F. A., & Atoyan, A. M. 1996, A&A, 309, 917
Aharonian, F. A., Akhperjanian, A. G., Barres de Almeida, U., et al. 2008a, A&A, 477, 353
Aharonian, F. A., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2008b, A&A, 481, 401
Atoyan, A. M., Aharonian, F. A., & Völk, H. J. 1995, Phys. Rev. D, 52, 3265
Atwood, W. B., Abdo, A. A., Ackermann, M., et al. 2009, ApJ, 697, 1071
Bykov, A. M., Chevalier, R. A., Ellison, D. C., & Uvarov, Y. A. 2000, ApJ, 538, 203
Caprioli, D., Amato, E., & Blasi, P. 2010, Astropart. Phys., 33, 160
Castelletti, G., Dubner, G., Brogan, C., & Kassim, N. E. 2007, A&A, 471, 537
Castro, D., & Slane, P. 2010, ApJ, 717, 372
Dame, T. M., Elmegreen, B. G., Cohen, R. S., & Thaddeus, P. 1986, ApJ, 305, 892
Dame, T. M., Hartmann, D., & Thaddeus, P. 2001, ApJ, 547, 792
Ellison, D. C., & Bykov, A. M. 2011, ApJ, 731, 87
Fujita, Y., Ohira, Y., & Takahara, F. 2010, ApJ, 712, L153
Gabici, S., Aharonian, F. A., & Casanova, S. 2009, MNRAS, 396, 1629
Giuliani, A., Cardillo, M., Tavani, M., et al. 2011, ApJ, 742, L30
Green, D. A. 2009, MNRAS, 399, 177
Handa, T., Sofue, Y., Nakai, N., Hirabayashi, H., & Inoue, M. 1987, PASJ, 39, 709
Malkov, M. A., & O'C Drury, L. 2001, Rep. Prog. Phys., 64, 429
Mattox, J. R., Bertsch, D. L., Chiang, J., et al. 1996, ApJ, 461, 396
Nolan, P., et al. 2012, ApJS, in press (arXiv:1108.1435)
Ohira, Y., Murase, K., & Yamazaki, R. 2010, A&A, 513, 17
Ohira, Y., Murase, K., & Yamazaki, R. 2011, MNRAS, 410, 1577
Paron, S., & Giacani, E. 2010, A&A, 509, L4
Ptuskin, V. S., Moskalenko, I. V., Jones, F. C., Strong, A. W., & Zirakashvili, V. N. 2006, ApJ, 642, 902
Ptuskin, V. S., & Zirakashvili, V. N. 2005, A&A, 429, 755
Reach, W. T., Rho, J., & Jarrett, T. H. 2005, ApJ, 618, 297
Rodriguez Marrero, A. Y., Torres, D. F., de Cea del Pozo, E., Reimer, O., & Cillis, A. N. 2008, ApJ, 689, 213
Seta, M., Hasegawa, T., Dame, T. M., et al. 1998, ApJ, 505, 286
Torres, D. F., Li, H., Chen, Y., et al. 2011, MNRAS, 417, 3072
Uchiyama, Y., Blandford, R. D., Funk, S., Tajima, H., & Tanaka, T. 2010, ApJ, 723, L122
Uchiyama, Y. (on behalf of the *Fermi*-LAT Collaboration) 2011, in 25th Texas Symp. Relativistic Astrophysics, ed. F. M. Rieger, C. van Eldik, & W. Hofmann (Proc. Science; Trieste: SISSA), http://pos.sissa.it/archive/conferences/123/143/Texas 2010_143.pdf
Wolszczan, A., Cordes, J. M., & Dewey, R. J. 1991, ApJ, 372, L99