Fermi-LAT Discovery of Gamma-ray Emission from the SNR W51C Region

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Abstract**. It is widely believed that expanding shock fronts of supernova remnants (SNRs) are the principal sites for the production of galactic cosmic rays. The most straightforward step towards confirming this long-standing hypothesis is to search for neutral pion decay gamma-rays from SNRs, especially those interacting with a molecular cloud. We report on discovery of gamma-ray emission associated with the SNR W51C, which is known to be interacting with a molecular cloud, using the Large Area Telescope on board the Fermi Gamma-ray Space Telescope. Given the well-determined distance of $\simeq 6$ kpc, the gamma-ray emission from the SNR W51C region has the largest luminosity in gamma-rays among galactic sources.**

Keywords**: Fermi, gamma ray, supernova remnant**

I. Introduction

Galactic cosmic rays (GCRs) are widely believed to be accelerated in the expanding shocks of supernova remnants. This conjecture has been largely strengthened by recent observations of young SNRs in X-rays and very-high-energy (VHE) gamma-rays [1], [2]. *Chandra* X-ray observations of young SNRs have shown that the magnetic field at supernova shocks can be much stronger than what would be expected for shock compression of interstellar magnetic fields [3]. Such magnetic field amplification, realized as an integral part of efficient cosmic-ray acceleration at collisionless shocks, would make the maximum particle energy attainable at the shock large enough to explain the GCRs [4]. The strong magnetic fields inferred from X-ray observations prefer the hadronic origin of the VHE gamma-rays observed in young SNRs such as RX J1713.7−3946 [5] and Vela Jr [6]. Elucidating the gamma-ray emission mechanism at work, either of hadronic or leptonic origin, has been one of the most important challenges. The hadronic interpretation of the VHE gamma-rays (e.g., [7]) requires that a large fraction of kinetic energy released by an supernova explosion be transferred to cosmic rays.

If indeed efficient shock-acceleration at supernova shocks is responsible for the bulk of the GCRs, enhanced π^0-decay gamma-rays can be expected in those SNRs interacting with a molecular cloud [8], as a result of hadronic interactions between cosmic rays (mostly protons) and dense gas cloud. In this regard, recent VHE observations made with HESS of the SNR W28 [9] offer an interesting example of the VHE gamma-rays arising from a supernova shock–molecular cloud system. Since gamma-ray emission can be contributed also by high-energy electrons, via bremsstrahlung and/or inverse Compton processes, measuring a gamma-ray spectrum over as wide an energy coverage as possible is indispensable, if one attempts to identify the enhanced π^0-decay gamma-rays. The importance of the GeV domain should be emphasized by the prediction that the flux and spectrum of the GeV–TeV radiation from the cosmic-ray-illuminated cloud can significantly evolve both in space and time [10].

The advent of the Large Area Telescope (LAT) onboard the *Fermi* Gamma-ray Space Telescope [11] has just started to provide a new opportunity to study the gamma-ray emission from SNRs in 20 MeV–300 GeV, more than over three orders of magnitude in energy. The *Fermi* LAT collaboration has announced initial source lists that include the 205 most significant (greater than $\sim 10\sigma$) based on the first three months observations [12]. The bright source list includes position estimate and the integrated flux obtained by using power law models in two energy bands. The list includes 0FGL J1923.0+1411, which is spatially coincident with the SNR W51C. The LAT source was reported as $\sim 23\sigma$ detection ($\sqrt{\mathrm{TS}} = 23$, where $\mathrm{TS} = -2\ln[L_0/L]$ is the likelihood test statistics [13]), with gamma-ray flux of $F_{23} = (4.1 \pm 0.5) \times 10^{-7}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (100 MeV–1 GeV) and $F_{35} = (3.4 \pm 0.3) \times 10^{-8}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (1 GeV–100 GeV). In this paper, we report the results of detailed analysis on the LAT source spatially coincident with the SNR W51C.

II. SNR W51C

W51C (G49.2−0.7), situated at the tangential point ($l = 49°$) of the Sagittarius arm, is a radio-bright SNR at a distance of $\simeq 6$ kpc, with an estimated age of $\sim 2 \times 10^4$ yrs [14]. In the 330 MHz continuum image [15], the SNR W51C appears to have an elliptical shape with an extent of $\sim 0.8°$ (~ 80 pc at 6 kpc) along its major axis. The radio continuum emission is linearly polarized, and has shell-like structures. The SNR W51C emits thermal X-rays with a temperature of $kT \sim 0.3$ keV [16], [17]. Shell-like emission is also seen in X-rays, which is similar to the radio shells. There is a good match between the X-ray and radio boundaries.

W51C undergoes a molecular cloud–shock interaction, as evidenced by observations of shocked atomic and molecular gases [14], [18]. The structure of the shocked HI gas is composed of a strong peak that encloses the most of the shocked HI gas and an extended envelope. Associated with the shocked HI gas, there found shocked molecules: CO and HCO^+. The shocked HI and molecules can be explained by a shock driven by the SNR and propagating into the molecular cloud.

The SNR W51C is superposed by the thermal radio complex W51B, a massive star-forming region which includes HII regions G48.9−0.3, G49.1−0.4, and G49.2−0.4. The W51 complex is considered to be in the early stage of forming an OB association. The molecular cloud that is interacting with the SNR W51C would be part of the star-forming cloud.

III. Observation and Data Reduction

The *Fermi* Gamma-ray Space Telescope was launched on 2008 June 11 by a Delta II Heavy launch vehicle. The Large Area Telescope (LAT) onboard *Fermi* is a pair-conversion gamma-ray detector capable of measuring gamma-rays in a very wide range of energy (0.02–300 GeV). The LAT tracks the electron and positron resulting from pair conversion of an incident gamma-ray in a thin high-Z foil, and measures the energy deposition due to the subsequent electromagnetic shower that develops in the calorimeter. The LAT has a wide field of view of $\int A_{\rm eff}(\theta,\phi)d\Omega/A_{\rm eff}(0,0) \simeq 2.4$ sr at 1 GeV, where $A_{\rm eff}$ is the effective area after all cuts made, and observes the entire sky about every 2 orbits (~ 3 hr for *Fermi*'s orbit at ~ 565 km). It has a large effective area ($\sim 8000\ {\rm cm}^{-2}$ above 1 GeV if on-axis) and a good angular resolution (a 68% containment radius of 0.8° at 1 GeV). After an initial checkout phase that includes instrument turn-on and on-orbit calibration [19], the LAT has been operating in sky survey mode since the beginning of 2008 August. The full details of the instruments as well as data processing are given in [11].

We analyzed the *Fermi* LAT gamma-ray data around the SNR W51C region, accumulated for eight months from 2008 August 15 to 2009 April 15. We chose *diffuse* class events [19], which are used for the most of LAT gamma-ray analysis (except for gamma-ray bursts) to optimize a balance between the effective area and residual background rate. Earth zenith angle (the angle of the photon's reconstructed direction from the Earth-spacecraft vector) cuts were applied to eliminate Earth albedo gamma-rays, by selecting photons with the angle smaller than 105°.

The tracker of the LAT is divided into two regions, *front* and *back*. The front region (first 12 planes) has thin converters each with 0.03 radiation lengths to optimize the PSF at low energy, while the back region (4 planes after the front section) has thicker converters to enlarge the effective area. The angular resolution of the back events is a factor of two worse than that of the front events at 1 GeV. For imaging analysis, where angular resolution is crucial, we make use of the front events in this paper.

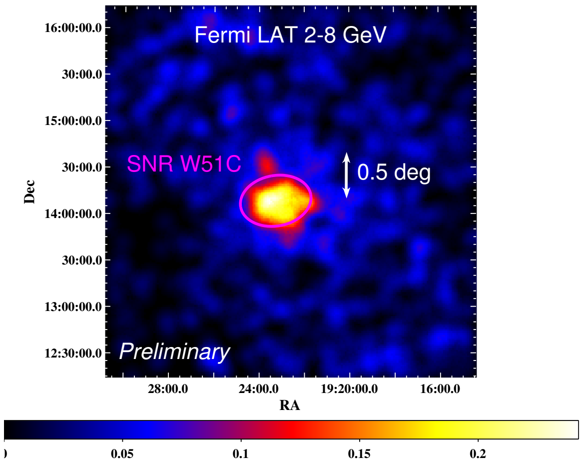

Fig. 1. *Fermi* LAT counts map in 2–100 GeV around the SNR W51C. Gaussian smoothing with $\sigma = 0.16^\circ$ is applied. The outer boundary of the SNR, as determined by the X-ray and radio images, is drawn as a dashed ellipse.

IV. Analysis and Results

In Figure 1, the LAT counts maps in the 2–100 GeV band centered on the SNR W51C are shown. As mentioned above, in order to obtain the best quality image, we selected *front* events. The counts maps are smoothed by an energy-independent Gaussian kernel with $\sigma = 0.16^\circ$, which is comparable to the PSF at 2 GeV. The color scale shows counts per pixel with a pixel size of 0.02°. The position of the LAT source at the center of Figure 1 indeed coincides well with the position of the SNR W51C seen in the X-ray and radio bands. The observed gamma-rays from the SNR W51C region well exceeds the galactic diffuse emission in this energy band.

A zoom-in view of the LAT counts map around the SNR W51C in the 2–100 GeV band is shown in Figure 2. The ROSAT X-ray map [16] (contours) is overlaid on the LAT counts map. Analysis of X-ray spectra obtained with *ASCA* and *Chandra* indicate that the X-ray emission seen in the ROSAT map comes from isothermal plasma with a temperature of $kT \sim 0.3$ keV [16], [17]. The LAT source peak coincides roughly with the X-ray enhanced region. The LAT PSF is drawn in Figure 2. It was constructed by assuming an energy spectrum of a power law with photon index 2.5 that was determined by maximum likelihood analysis in this band. The PSF is then smoothed by a Gaussian kernel with $\sigma = 0.16^\circ$, to be compared with the smoothed counts map. The gamma-ray (> 2 GeV) distribution of the SNR W51C region appears significantly extended beyond the PSF.

We use the maximum likelihood technique for spectral parameter estimation with a tool GTLIKE, which is part of the standard, publicly available, science software package developed by the *Fermi* LAT collaboration. The results of our spectral analysis will be presented at the

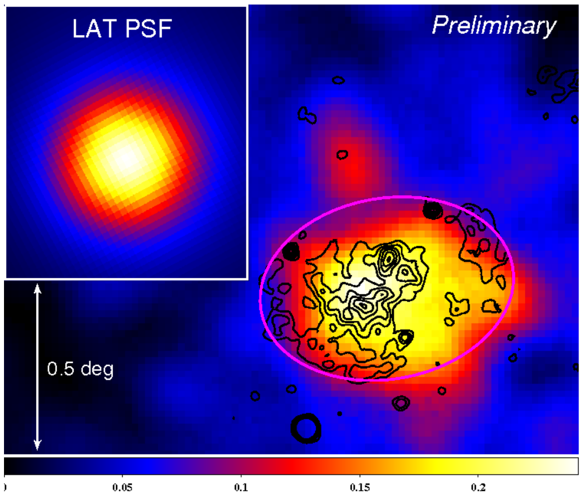

Fig. 2. Zoom in view of Fig. 1. The ROSAT X-ray map (contours) is superposed. The SNR boundary is drawn as a dashed ellipse.

conference.

V. Discussion

The gamma-ray emission associated with the SNR W51C has been studied using the *Fermi* LAT. The gamma-ray emission is spatially extended beyond the PSF of the LAT and is consistent with the extent of the SNR W51C. This precludes the possibility that the gamma-ray source associated with the SNR W51C is due to a pulsar. Using the large distance of 6 kpc to the remnant, the gamma-ray luminosity can be calculated as $\sim 6 \times 10^{35}$ erg s^{-1}. The importance of the LAT result would be emphasized by the fact that the gamma-ray luminosity overwhelms the well-known young SNR RX J1713.7−3946 by nearly two orders of magnitude. W51C becomes one of the most luminous gamma-ray sources among galactic objects. Most recently, the H.E.S.S. collaboration announced the detection with a statistical significance of 6.7 σ of a new source: HESS J1923+141. The source is extended compared to the H.E.S.S. PSF and it is spatially coincident with the SNR W51C. The integrated flux over 1 TeV is equivalent to $\sim$3% of the flux of the Crab Nebula above the same energy [20].

The SNR W51C is interacting with the giant molecular cloud as evidenced by two 1720 MHz OH masers which have been detected in the north part of the shell [21] and by detections of shocked atomic and molecular gases [14], [18]. The GeV emission seen by the *Fermi* LAT in the SNR W51C region, and the TeV gamma-rays detected by H.E.S.S., may emerge as a result of supernova shock–cloud interactions. (Note however that a possible pulsar wind nebula around an X-ray source CXO J192318.5+140505 [17] would be responsible for the TeV emission.) Discussion on the origin of the gamma-rays and implications to cosmic-ray acceleration will be given at the conference.

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