SUPERNova REMNANT KESTeven 27: INTERACTION WITH A NEIGHBOR Hi CLOUD VIEWED BY FERMI

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ABSTRACT

We report on the likely detection of γ-ray emission from the supernova remnant (SNR) Kesteven 27 (Kes 27). We analyze 5.7 yr Fermi Large Area Telescope data of the SNR region and find an unresolved source at a position consistent with the radio brightness peak and the X-ray knot of Kes 27, which is located in the eastern region of the SNR and caused by its interaction with a nearby H I cloud. The source’s emission is best fit with a power-law spectrum with a photon index of 2.5 ± 0.1 and a >0.2 GeV luminosity of 5.8 × 10^{34} erg s^{-1} assuming a distance of 4.3 kpc, as derived from radio observations of the nearby H I cloud. Comparing the properties of the source with that of other SNRs that are known to be interacting with nearby high-density clouds, we discuss the origin of the source’s emission. The spectral energy distribution of the source can be described by a hadronic model that considers the interaction of energetic protons escaping from the shock front of Kes 27 with a high-density cloud.

Key words: acceleration of particles – gamma rays: ISM – ISM: individual objects (Kesteven 27) – ISM: supernova remnants

1. INTRODUCTION

The high sensitivity and fine spatial resolution of the Fermi Gamma-ray Space Telescope, combined with that of ground-based very high energy γ-ray telescopes, have allowed us to conduct a study in unprecedented detail of supernova remnants (SNRs) at high-energy GeV and TeV energies. From Fermi observations, we now know that due to their interaction with nearby molecular clouds (e.g., Ferrand & Safi-Harb 2012), middle-aged SNRs, such as W51C (Abdo et al. 2009), W44 (Abdo et al. 2010d), IC 443 (Abdo et al. 2010e), and W28 (Abdo et al. 2010a), are among the brightest MeV to GeV γ-ray sources, having γ-ray luminosities of ~10^{36} erg s^{-1}. In comparison, young SNRs with ages no greater than a few thousand years, such as RX J1713.7-3946 (Ellison et al. 2010; Abdo et al. 2011), Cas A (Abdo et al. 2007b), and Tycho (Acciari et al. 2011), have γ-ray luminosities two orders of magnitude lower. γ-ray emission from dynamically evolved SNRs interacting with molecular clouds is believed to be dominated by pion decay emission, resulting from the collision of relativistic protons with ambient material (e.g., Abdo et al. 2009, 2010a, 2010d, 2010e). Their high luminosities rule out the alternative of a leptonic origin, since the required total electron energy would be >10^{51} erg, larger than the typical kinetic energy released by a supernova explosion (e.g., Abdo et al. 2010a). In the leptonic scenario, the high-energy emission is thought to be due to either inverse Compton up-scattering of ambient low-energy photons by relativistic electrons or Bremsstrahlung radiation from high-energy electrons. Even among young (≤2000 yr) SNRs, there is sometimes also evidence suggesting a hadronic origin to the observed γ-ray emission. The position of the γ-ray emission may coincide with the region in an SNR which is known to be interacting with a nearby molecular cloud (e.g., Xing et al. 2014). In this paper, we report the Fermi detection of another such case, the SNR Kesteven 27 (Kes 27).

As a thermal composite SNR, Kes 27 (also known as G327.4 +00.4) was found to be confined to an H I shell interacting with a nearby H I cloud to the southeast (McClure-Griffiths et al. 2001), leading to a radio brightness peak at the southeast edge of Kes 27 (Milne et al. 1989; McClure-Griffiths et al. 2001). The extent of the SNR’s radio emission is approximately ~21′ as measured with the Molonglo Observatory Synthesis Telescope (MOST) at 843 MHz (Whiteoak & Green 1996). A kinematic distance of approximately 4.3 ± 0.5 kpc was estimated for the H I cloud, and thus for Kes 27, derived from the velocity measurements from the H I absorption spectra in their direction (McClure-Griffiths et al. 2001). Kes 27 has also been observed at X-ray energies with different X-ray telescopes including Einstein (Lamb & Markert 1981; Seward 1990), ROSAT (Seward et al. 1996), ASCA (Enoguchi et al. 2002; Kawasaki et al. 2005), and Chandra (Chen et al. 2008). Slightly different from other thermal composite SNRs whose X-ray emission is centrally peaked, high-spatial Chandra imaging has revealed that this SNR has bright emission in the region east of its center and that the emission near the eastern shell roughly coincides with the radio morphology (Chen et al. 2008). The X-ray imaging thus also indicates enhanced emission due to the interaction with the H I cloud. From X-ray observations of the diffuse emission from Kes 27, a dynamical age of ~8000 yr was derived for the SNR, adopting a shock velocity of 580 km s^{-1} and a diameter of 20′ (Chen et al. 2008).

In this paper, we report our analysis of the Fermi Large Area Telescope (LAT) data of the Kes 27 region and the likely detection of γ-ray emission from the interaction region of the SNR. We describe the Fermi observation data in Section 2 and present our data analysis and results in Section 3. The results are discussed in Section 4.

2. OBSERVATION

As the main instrument on board the Fermi Gamma-ray Space Telescope, LAT is a γ-ray imaging instrument that scans the whole sky every three hours which can conduct long-term γ-ray observations of sources in the energy range from 20 to
300 GeV (Atwood et al. 2009). In our analysis, we selected LAT events from the Fermi Pass 7 Reprocessed (P7REP) database inside a 20° × 20° region centered on the position of Kes 27. The SIMBAD position of Kes 27 is R.A. = 237:1583, decl. = −53:7867 (equinox J2000.0), which was adopted as the central position of Kes 27 after comparison with the radio (Milne et al. 1989) and X-ray maps (Seward et al. 1996; Enoguchi et al. 2002; Chen et al. 2008) of this source. We retained events during the time period from 2008 August 04 15:43:36 (UTC) to 2014 April 13 22:13:17 UTC, and rejected events below 200 MeV because of the relatively large uncertainties of the instrument response function of the LAT in the low-energy range. In addition, following the recommendations of the LAT team4, we included those events with zenith angles less than 100°, which prevents the Earth’s limb contamination, and those events during good time intervals when the quality of the data was not affected by the spacecraft events.

3. ANALYSIS AND RESULTS

3.1. Source Detection

We included all sources within 16° centered on the position of Kes 27 in the Fermi 2 yr catalog (Nolan et al. 2012) when creating the source model. The spectral function forms of these sources are provided in the catalog. The spectral normalizations of the sources within 8° of Kes 27 were set as free parameters, and the other parameters were fixed at their catalog values. In addition, the γ-ray pulsar PSR J1543–5149 (Ng et al. 2014) was included in the source model, although it was not listed in the catalog. We modeled the pulsar’s emission using a power law with an exponential cutoff, which is the characteristic spectrum for pulsar emission, and set the spectral normalization, spectral index, and cutoff energy as free parameters. The Galactic and extragalactic diffuse emission were also added to the source model using the spectral model gll_iem_v05.fits and the file iso_source_v05.txt, respectively. The normalizations of the diffuse components were free parameters.

We performed standard binned likelihood analysis on the LAT data in the >0.2 GeV range using the LAT science tools software package v9r23p5, and extracted the Test Statistic (TS) map of a 5° × 5° region centered on the position of Kes 27. A TS map that included sources in the source model outside of the region was made, and is shown in the left panel of Figure 1. The TS map indicates that Kes 27 is located in a complex region with two nearby catalog sources, 2FGL J1554.4–5317c and 2FGL J1551.3–5333c. Then, removing all of the sources in the source model in this region, a residual map was made and is shown in the right panel of Figure 1. Excess γ-ray emission appears near the center with TS ≃ 217, indicating ∼15σ detection significance. For these analyses, we also tested to included sources within 20° centered at Kes 27 and free the spectral indices of the sources within 5° from Kes 27, but the results of the source positions and spectra did not show significant differences (consistent within uncertainties), and in the Kes 27 region TS ≃ 200, only slightly lower than that from fixing the spectral indices.

While Lande et al. (2012) analyzed the two nearby sources 2FGL J1554.4–5317c and 2FGL J1551.3–5333c, and determined that they did not have extended emission, we also investigated whether or not the excess emission could be due to any confusion because of the proximity to 2FGL J1551.3–5333c. Different TS maps in the energy ranges of >1 GeV, >2 GeV, and >3 GeV were made, as the point-spread functions (PSFs) of LAT are significantly reduced at higher energies.5 To make the TS maps, all of the sources in the source model, except for 2FGL J1551.3–5333c, were removed. We found that the excess emission is clearly resolved from 2FGL J1551.3–5333c. A TS map of the source region in 3–300 GeV is displayed in the left panel of Figure 2, showing that they are separate. In fact, in the high-energy range, the catalog position

4 http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools

5 http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm
of 2FGL J1551.3–5333c, having TS ≃ 34, is not at the TS peak (∼48). There may be another source east of 2FGL J1551.3–5333c. We tested to determine the position for this source in the 3–300 GeV range and obtained R.A. = 238°22, decl. = −53°61, with a large uncertainty of 0.26 (1σ). The position is offset from 2FGL J1551.3–5333c, and therefore they are consistent within the uncertainty. No conclusion could be made for them based on the current data. In any case, the excess emission in the Kes 27 region was always present in these analyses.

Examining the excess emission in the high-energy range, we found that it actually consists of two individual sources. The 1° × 1° residual TS map of the region centered on Kes 27 (right panel of Figure 2), which was made using >3 GeV data, shows the details. Two possible sources are resolved, with the southeast and northwest sources marked as A and B, respectively. The TS values for these sources are ≃22 and ≃14, respectively. While source B dominates the emission in the >0.2 GeV energy range (see Section 3.3), source A is significantly detected in the >3 GeV energy range. We overlaid the radio intensity contours for Kes 27, detected by MOST at 843 MHz (Whiteoak & Green 1996), onto the map and found that the radio brightness peak of Kes 27 is located close to the southeast source. By running gfindsrc in the LAT software package, we determined its position, which is R.A. = 237°37, decl. = −53°88, (equinox J2000.0), with 1σ nominal uncertainty of 0:04. This position is consistent with that of the radio brightness peak of Kes 27 (approximately R.A. = 237°33, decl. = −53°82) within the 2σ error circle. The positional coincidence suggests that source A is likely associated with Kes 27. Below, we consider this source as the γ-ray counterpart to Kes 27 (see also the Discussion section).

For source B, we also obtained its best-fit position in the >3 GeV energy range, and the position is R.A. = 236°86, decl. = −53°67 with a 1σ nominal uncertainty of 0:08. We tested to consider and remove this source from the >3 GeV TS map, and the excess γ-ray emission (i.e., source A) at the southeast region of Kes 27 was still present with TS ≃ 20.

We thus added these two sources at their best-fit positions to the source model and performed a binned likelihood analysis in the >0.2 GeV range. Their spectra were modeled using a power law. We found that sources A and B have photon indices of Γ = 2.5 ± 0.1 (with a TS value of ∼76) and Γ = 2.7 ± 0.1 (with a TS value of ∼80), respectively.

Source B could be emission from Kes 27 as well, since it positionally coincides with the northwest part of Kes 27 (Figure 2). However, given the radio and X-ray morphology of the SNR, no notable features were seen at the source’s position, and it would be hard to explain why the SNR is bright in this source region but not in the whole region if the SNR has significant γ-ray emission. In the Chandra observation reported by Chen et al. (2008), an X-ray point source, CXOU J154816.7−534125, was detected at the position of R.A. = 237°0700, decl. = −53°6904 (0.5σ uncertainty). This source (marked by a green cross in the right panel of Figure 2) is 0:12 away from the best-fit position of source B but within the 2σ error circle. It was thought to be a background candidate active galactic nucleus (AGN). As AGNs generally have a power-law γ-ray spectrum with photon index up to 3.0 in the Fermi γ-ray energy range (Abdo et al. 2010), the spectrum of source B also suggests the possible association between them (for source B’s spectrum, see Section 3.3).

3.2. Spatial Distribution Analysis

We analyzed the spatial distribution of the Kes 27 counterpart to determine whether it is point-like or extended. We used both point-source and uniform disk models with power-law spectra at the best-fit position to analyze the emission in the

Figure 2. Left panel: TS map of the 2° × 2° region centered at R.A. = 237°1583, decl. = −53°7867 (equinox J2000.0) in the 3–300 GeV range. The image scale of the map is 0.04 pixel. All sources except for 2FGL J1551.3–5333c were considered and removed. The symbols are the same as those in Figure 1, while the 2σ error circle for the nearby catalog source 2FGL J1551.3–5333c is marked by a green dashed circle. Right panel: Residual TS map of the 1° × 1° region centered at R.A. = 237°1583, decl. = −53°7867 (equinox J2000.0) in the 3–300 GeV range with the catalog source 2FGL J1551.3–5333c removed. The image scale of the map is 0.02 pixel. The black contours are the MOST 843 MHz radio contours (at square-root scale levels of 0.01, 0.02, 0.05, 0.10, 0.17, 0.25, and 0.36 Jy beam−1; Whiteoak & Green 1996). The dark and green dashed circles mark the 2σ error circles of the best-fit positions of the Kes 27 γ-ray emission and source B (see the text), respectively. The latter may be associated with a background candidate AGN (marked by the green cross; Chen et al. 2008).
3–300 GeV range. Source $B$ was included in the source model. The searched radius range for the uniform disks was 0.1–0.5 with a step of 0.1. Additionally, only front converting events for the instrument response function P7REP_SOURCE_V15:FRONT were included in the analysis, which allows us to reduce the PSF of the LAT point sources to <0:3 (68% containment) in the ≥3 GeV range. For the point source, we set the spectral normalizations of the sources within 8° from Kes 27 as free parameters, and fixed all other parameters in the source model at the Fermi 2 yr catalog values. The spectral indices of Kes 27 and source $B$, and the spectral index and cutoff energy of PSR J1543–5149 were fixed at the values obtained from likelihood analysis in the >0.2 GeV energy range. For the disk models, we fixed all of the spectral parameters of the sources in the source model to the values obtained above, but set the spectral normalization parameters of the disk models to be free. No significant extended emission was detected; $TS_{\text{ext}}$, values, calculated from $TS_{\text{disk}} - TS_{\text{point}}$, were smaller than 0.

### 3.3. Spectral Analysis

Considering the Kes 27 counterpart and source $B$ as point sources at their best-fit positions, their $\gamma$-ray spectra were extracted by performing maximum likelihood analysis of the LAT data in 10 evenly divided energy bands in logarithm from 0.1–300 GeV. By assuming a power law for emission in each energy band, the obtained fluxes are less model dependent, providing a good description for the $\gamma$-ray emission of a source. The source model included all of the sources in the Fermi 2 yr catalog and the pulsar J1543–5149. The spectral normalizations of the sources within 8° from Kes 27 were set as free parameters, while all of the other parameters of the sources were fixed at the values we obtained above in Section 3.1. We kept only those spectral flux points with TS greater than 4 (corresponding to a detection significance of 2σ), and derived 95% flux upper limits in the other energy bands. The obtained spectra of the counterpart to Kes 27 and source $B$ are shown in Figure 3, and the flux and uncertainty values are given in Table 1. From the flux measurements, we note that source $B$ was more significantly detected at energies of ≤1 GeV.

In addition to the statistical uncertainties obtained above, we note that the LAT effective area introduces approximately 5%–10% systematic uncertainties to the energy fluxes (Nolan et al. 2012; Abdo et al. 2013). There are also systematic uncertainties due to the Galactic diffuse emission model, which can be estimated from repeating the likelihood analysis in each energy band with the normalization of the diffuse component artificially fixed to the ±6% deviation from the best-fit value (see, e.g., Abdo et al. 2009, 2010a, 2010c). The uncertainties estimated in this way are provided in Table 1. They are the dominant uncertainties in the systematic uncertainties (Abdo et al. 2010a, 2013).

### 4. DISCUSSION

#### 4.1. Source Identification

Having analyzed 5.7 yr Fermi/LAT data of the Kes 27 region, we found a $\gamma$-ray source at the position consistent with that of the radio brightness peak of the SNR. The $\gamma$-ray source has power-law emission with a photon index of 2.5, and the total 0.2–300 GeV flux is approximately $2.6 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$. We performed a spatial distribution analysis in the >3 GeV energy range, but no significant extended emission was detected for the source. The >0.2 GeV detection significance of the source for a point-source profile at the best-fit position is ≈8σ.

The positional coincidence strongly suggests the association of the $\gamma$-ray source with Kes 27, the emission of which is enhanced and thus detectable due to the SNR’s interaction with a nearby dense cloud. The Fermi-detected SNRs interacting with dense clouds can appear to have prominent flux peaks around ~1 GeV, which can likely be explained by the hadronic scenario (e.g., Li & Chen 2012 and references therein): a cloud with high mass density acts as a large target for relativistic protons to interact with and decay into neutral pions and subsequently $\gamma$-rays. For example, the SNRs W44 (Giuliani...
to a fraction of the explosion energy converted into the protons’ energy \( \eta = 60\% \left( n_p/1\ cm^{-3} \right)^{-2}E_{51}^{-1} \) (where \( E_{51} \) denotes the supernova explosion energy in units of \( 10^{51}\ erg \)). This is plausible considering the presence of the surrounding dense H\textsc{i} gas, and especially the dense clump on the southeastern edge (McClure-Griffiths et al. 2001; Chen et al. 2008). If the hot gas density (as high as \( \gtrsim 2\ cm^{-3} \)) obtained from the X-ray emission along the eastern boundary (regions E1 and E2) can be a reference value for the target gas density, then the conversion fraction \( \eta \) would be in a moderate range within 30%. In this scenario, the proton index \( \alpha_p \) is the same as the \( \gamma \)-ray photon index, 2.5 \( \pm 0.1 \), as obtained from the spectral fit. This value seems slightly high compared to the 2.1–2.4 derived from the observed slope of the detected cosmic ray spectrum at Earth (Gabici 2013), and would be difficult to explain theoretically for the shock accelerated protons.

However, a high proton index can be naturally expected if the accelerated protons experience a diffusion process before they bombard the surrounding dense gas. The centroid of the \( \gamma \)-ray TS map is essentially located outside the southeastern boundary (see Figure 2) and appears to be coincident with the H\textsc{i} cloud to the southeast (McClure-Griffiths et al. 2001). Therefore, the adjacent cloud may be “illuminated” by the protons escaping from the SNR. A convenient algorithm has been established for such a bombardment for the illumination of an adjacent cloud by the diffusive energetic protons escaping from an expanding SNR shock front (Li & Chen 2010). In this scenario, at a given position for the dense cloud outside the SNR, the proton spectrum is obtained by accumulating the entire contribution of the escaping protons throughout the history of the SNR expansion. When this accumulative collection of diffusive protons collides with the nearby cloud, the \( \pi^0 \)-decay \( \gamma \)-rays emanate. The power-law index of the escaping protons will be higher than \( \alpha_p \) and approaches \( \alpha_p + \delta \) (Aharonian & Atoyan 1996), where \( \delta \) is the power-law index of the diffusion coefficient \( D(E_p) \sim E_p^{\delta} \), and \( \delta = 0.3–0.7 \), e.g., Berezinski et al. 1990). We refer to Li & Chen (2010) and references therein for details of the model.

In our calculation using the latter model, an age of \( \sim8000\ yr \) is adopted for SNR Kes 27. At a distance of 4.3 kpc, the SNR is \( \sim13\ pc \) in radius and the H\textsc{i} cloud is thus assumed to be \( R_{\text{cl}} \approx 13 \) pc away from the center of the SNR. Other parameters used in the calculation were the fraction of the explosion energy converted into accelerated protons \( \eta = 0.1 \) (Blandford & Eichler 1987), the spectral index for the energy distribution of the protons \( \alpha_p = 2.2 \) (e.g., Giuliani et al. 2010), and the correction factor of slow diffusion around the SNR \( \chi = 0.1 \) (Fujita et al. 2009). The parameters \( \chi \) and \( \delta \) determine the diffusion coefficient, and thus the diffusion radius in the model. In the calculation fitting the observed \( \gamma \)-ray spectrum, \( \delta = 0.4 \) and a total cloud mass of \( M_{\text{cl}} \approx 200E_{51}^{-1}\ M_\odot \) are required. The model spectrum is shown in Figure 4. The model cloud mass is consistent with the observation. Actually, according to McClure-Griffiths et al. (2001), the bulk (including the core) of the H\textsc{i} cloud on the southeast appears to be outside the SNR’s edge. The hot gas density is \( \gtrsim 2\ cm^{-3} \) in region E1 (Chen et al. 2008) and may be no higher than the average gas density of the cloud, since this region is likely in the outer part of the cloud. Therefore, the cloud, \( \sim0.1 \) in angular radius, may thus have a mass of \( \gtrsim 120\ M_\odot \). We note that our model spectrum is slightly lower than the sensitivity limit of HESS (Aharonian et al. 2006; see Figure 4), which may explain the non-detection of Kes 27 at TeV.
energies in the HESS Galactic plane survey (Carrigan et al. 2013). Considering the much improved sensitivity of the Cherenkov Telescope Array (CTA), the Fermi detection of Kes 27 can be confirmed by CTA observations, and the model used here may also be tested or constrained.

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Figure 4. Fermi γ-ray spectrum of Kes 27. The statistical and systematic uncertainties are shown as solid and dotted bars, respectively. The hadronic model (solid curve; Li & Chen 2010) can reproduce the observed emission. The blue and pink dashed curves indicate the sensitivity limits of HESS and CTA, respectively.

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