1. INTRODUCTION

The origin of cosmic rays (CRs) remains one of the most debated issues in high energy astrophysics more than 100 years after they were first detected. Supernova remnants (SNRs), whose strong shocks contain huge amounts of energy, are considered to be the most probable candidates among Galactic CR acceleration sources (e.g., Ginzburg & Syrovatskii 1969). A long standing argument concerning the putative SNR-CR link is that non-thermal radio emission from SNRs provides clear evidence for electron acceleration, whereas the CR spectrum observed on Earth is 99% protons and other nuclei. Therefore, the \( \gamma \)-ray emission from SNRs dominated by the decay of \( \pi^0 \) mesons produced via proton–proton collisions (i.e., the hadronic interaction) plays a key role in providing evidence for proton acceleration (Ackermann et al. 2013). However, it is often difficult to distinguish between the hadronic \( \gamma \)-ray emission and the electrons’ inverse Compton or non-thermal bremsstrahlung emission (i.e., the leptonic emission). There are generally two scenarios that describe how hadronic \( \gamma \)-rays are produced in SNRs. In one scenario, the \( \pi^0 \)-decay emission is suggested to arise from shock-crushed dense clouds where the accelerated protons frozen in the clouds efficiently collide with target cloud gas (e.g., Blandford & Cowie 1982; Uchiyama et al. 2010; Tang & Chevalier 2014). In the other scenario, the hadronic \( \gamma \)-rays are ascribed to interactions between the relativistic protons escaping from the SNR shock and adjacent molecular clouds (MCs; e.g., Aharonian & Atoyan 1996; Gabici et al. 2009; Li & Chen 2010; Ohira et al. 2011). In both scenarios, the SNRs interacting with MCs are crucial probes in the search for the signatures of proton acceleration. The hadronic \( \gamma \)-ray emission from SNR-MC systems is usually bright around GeV, and a series of GeV-bright SNRs interacting with MCs have recently been discovered with the Large Area Telescope (LAT) on board the Fermi Gamma-ray Space Telescope. These SNRs include W51C (Abdo et al. 2009), W44 (Abdo et al. 2010c), IC 443 (Abdo et al. 2010d), W28 (Abdo et al. 2010a), W41 (Castro et al. 2013), RCW 103 (Xing et al. 2014), etc. Additional GeV observations continue to enlarge the sample of hadronic interaction between SNRs and MCs, and here we present a GeV study of another SNR, namely, Kesteven 41 (G337.8–0.1). As a southern-sky SNR, Kes 41 is shown to be centrally brightened in X-rays within a distorted radio shell by an XMM-Newton observation (Combi et al. 2008), and therefore is classified as a thermal composite (or mixed-morphology) SNR (Jones et al. 1998; Rho & Petre 1998). The X-ray emitting plasma of the SNR has been newly revealed to be rich in sulfur and argon; thus, Kes 41 joins the subclass of “enhanced-abundance” or “ejecta-dominated” thermal composites (Zhang et al. 2015). Kes 41 has also been found to be interacting with an adjacent MC, as indicated by the 1720 MHz hydrogen radical (OH) maser emission detected in the northern radio shell (Koralesky et al. 1998; Caswell 2004). Recently, we found that Kes 41 is associated with a giant MC at a systemic local standard of rest (LSR) velocity of \( -50 \) km s\(^{-1} \) and is confined in a cavity delineated by a northern molecular shell, a western concave MC, and a southeastern H\(_{2}\) cloud (Zhang et al. 2015). The forward shock is suggested to have left the...
adiabatic stage since the SNR shock encountered the cavity wall, while the inner thermal X-rays are ascribed to heating by the reflection shock from the cavity wall. The birth of Kes 41 inside the molecular cavity provides a mass estimate of \( \gtrsim 18M_\odot \) for the stellar progenitor. It is logical and meaningful to search for hadronic emission due to the interaction of the SNR with the dense environmental gas.

In this paper, we report the results from a spatial and spectral analysis of the Fermi-LAT observation data of the Kes 41 region. We describe the Fermi observation data in Section 2 and present the data analysis and results in Section 3. The possible physical relation of the detected \( \gamma \)-ray emission with the SNR is discussed in Section 4.

2. OBSERVATIONS AND DATA REDUCTION

The LAT on board Fermi, launched on 2008 June 11, is a \( \gamma \)-ray imaging instrument that covers a very wide range of energy from 20 MeV to 300 GeV. It reconstructs the direction of incident \( \gamma \)-rays by tracking the electrons and positrons resulting from pair conversion of the \( \gamma \)-rays in the solid state silicon trackers, and measures the energy of the subsequent electromagnetic showers that develop in the cesium iodide calorimeters (Atwood et al. 2009). The point-spread function (PSF) varies largely with photon energy and improves at high energies (the 68\% containment radius at \( >2 \text{ GeV} \) is smaller than 0.5\); Atwood et al. 2009).

We use the reconstructed Pass 7 reprocessed version of 5.6 years of accumulated Fermi-LAT data\(^8\) that has been selected from 2008 August 04 15:43:37 (UTC) to 2014 April 01 02:29:28 (UTC). We analyze the data with the standard software, ScienceTools version v9r32p5\(^7\) released on 2013 October 24, with the instrument response functions P7REP_SOURCE_V15. Standard selection criteria are applied to the data selection process as described below. The Source (evclass=2) events are selected and the maximum zenith angle cut is 100\(^\circ\) to reduce the residual \( \gamma \)-rays from CR interactions in the upper atmosphere. We used the standard criteria for selecting time intervals for our analysis: (DATA_QUAL==1) & (LAT_CONFIG==1) & (ABS(ROCK_ANGLE) < 52.\). The analysis is restricted to the energy range above 200 MeV due to uncertainties in the effective area and broad PSF at low energies and below 300 GeV due to limited statistics.

3. ANALYSIS AND RESULTS

In our analysis, we select the LAT events inside a \( 14^\circ \times 14^\circ \) region of interest (ROI, in equatorial coordinate system) centered at the position of Kes 41 (R.A. (J2000) = 16\( ^{h} \)39\( ^{m} \)00\( ^{s} \)) and decl. (J2000) = \(-46^\circ 58' 59"\)) with a bin size of 0.04\(^\circ \times 0.04\(^\circ \). We perform our analysis following the standard binned likelihood analysis procedure. The second Fermi-LAT Catalog (2FGL) sources (Nolan et al. 2012) within radius 15\(^\circ\) around Kes 41 are included in the source model, which was generated by the user-contributed software make2FGLxml.py.\(^8\) The Galactic and extragalactic diffuse background components (as specified in the files gll_Iem_v05.fits and iso_source05.txt, respectively) are used. In the likelihood fittings, the spectral parameters of the sources located beyond 10\(^\circ\) of the ROI center are fixed to the values reported in 2FGL, and the spectral parameters of all the sources located within 10\(^\circ\) of the center of ROI together with the normalizations of the two diffuse backgrounds, are allowed to vary. The fittings are performed with the optimizer NEWMINUIT until convergence is achieved.

3.1. Source Detection

First, a binned likelihood analysis is applied in the energy range 2–300 GeV. In the source model, the source 2FGL J1638.0–4703c, which is very close to Kes 41, has been removed due to the uncertainty of its spatial and spectral information caused by the imperfectly modeled diffuse emission, and thus needs to be treated with great care\(^9\) (Nolan et al. 2012). A newly discovered \( \gamma \)-ray source (HESS J1641–463; Lemoine-Gouard et al. 2014) has been added assuming a power-law spectrum. Then, the test statistic (TS), defined as \( 2(\log \mathcal{L} - \log \mathcal{L}_0) \), where \( \mathcal{L}_0 \) is the likelihood of null hypothesis and \( \mathcal{L} \) is the likelihood with the source included) map for a \( 1^\circ \times 1^\circ \) region centered at Kes 41 is made after subtracting this baseline model (see Figure 1). As can be seen in Figure 1, there is excess \( \gamma \)-ray emission in the region of Kes 41. The position of the peak of the TS value is on the northwest of the SNR, but does not agree with the position of 2FGL J1638.0–4703c. It is generally consistent with the location of the dense MC at \( V_{\text{LSR}} \sim -50 \text{ km s}^{-1} \) which is found to be associated with the SNR (Zhang et al. 2015). We also perform an analysis in the low energy range 0.2–2 GeV, and some residual \( \gamma \)-ray emission is detected at the same position. Therefore, we add a point source with a power-law

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\(^{8}\) http://fermi.gsfc.nasa.gov/ssc/data

\(^{7}\) See http://fermi.gsfc.nasa.gov/ssc.

\(^{8}\) http://fermi.gsfc.nasa.gov/ssc/data/analysis/user/

\(^{9}\) http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2yr_catalog/
spectrum at the position where the TS value is highest in our source model to approximate the excess emission. After that, we conduct a binned likelihood analysis in the broad energy range 0.2–300 GeV and, utilizing gfindsrc (a tool in the LAT software package ScienceTools), we find the best-fit position of the excess γ-ray emission at (R.A. (J2000) = 16°38′36″00, decl. (J2000) = −46°55′06″96) with 1σ nominal uncertainty of 0.03 and 3σ nominal uncertainty of 0.09.

By comparison, we detect this source as a point-like source with a power-law spectrum in 0.2–300 GeV with a significance of 24σ at the best-fit position and increases the significance by 1σ over the position of 2FGL J1638.0–4703c. The data we use are collected from 5.6 years of Fermi-LAT observations while the tentative source 2FGL J1638.0–4703c was suggested based on the first two years of observations. Both the statistical result and increased exposure time suggest that the γ-ray emission excess at the best-fit position adjacent to Kes 41 is more significant than 2FGL J1638.0–4703c. Thus, we replace 2FGL J1638.0–4703c with this new source at the best-fit position (hereafter source A) in the following analysis.

In an attempt to explore the origin of the γ-ray emission of source A, we searched the SIMBAD Astronomical Database (Wenger et al. 2000) within a 3σ error circle of the source (see Figure 1). In addition to SNR Kes 41, only nine dark clouds, a young stellar object candidate, and an infrared source are known to exist in the region. Therefore, the origin of this γ-ray emission is most likely related to the SNR.

3.2. Timing Analysis

We next search for long-term variability in the one month binned light curve of source A in the energy range 0.2–300 GeV, which is obtained from likelihood analysis (Nolan et al. 2012) in each time bin. As can be seen in the light curve (Figure 2), all of the flux points remain within 3σ uncertainties of the average flux. Fitting the flux points with a TS value >4 to a constant flux model (shown as a red line in Figure 2) yields a χ² ~ 32.3 with 48 degrees of freedom (dof). Moreover, we calculate the Variability Index, TSvar, of source A (with all 69 time bins) in the 0.2–300 GeV energy range according to the method introduced in section 3.6 of Nolan et al. (2012). If the flux is constant, then TSvar is distributed as χ² with 68 dof, and variability would be considered probable when TSvar could exceed the threshold of 98.0 corresponding to 99% confidence. The computed TSvar of source A is 65.2, corresponding to a confidence level <50% for a variable source. These results suggest that there is no significant long-term variability observed in the region of Source A in the 0.2–300 GeV energy range. On the other hand, we construct 1000 s binned light curves of source A in the same energy range which are obtained through Fermi-LAT aperture photometry analyses10 using LAT photons within different aperture radius from 0.2′ to 0.5′. We analyze these light curves for periodic signals, but no significant periodicity is detected. However, this method is statistically limited and the periodicity is hard to detect due to the massive diffuse background photons in a low galactic latitude.

There is a close positional correspondence between source A, suggested here as a steady source, and 3FGL J1638.6–4654, which is indicated as a variable source in the third Fermi-LAT Catalog (3FGL) (Acero et al. 2015). 3FGL J1638.6–4654 is detected in 0.1–300 GeV with a significance of 13σ and a 0.1–300 GeV energy flux ~7.3 × 10⁻¹¹ erg cm⁻² s⁻¹; source A has a higher significance (24σ) with an energy flux of ~7.5 × 10⁻¹¹ erg cm⁻² s⁻¹ in the 0.2–300 GeV energy range (see Section 4.1; the flux will be somewhat higher in 0.1–300 GeV). The use of different spectral models and different energy ranges in the two timing analyses may contribute to the discrepancy in the variability between source A and 3FGL J1638.6–4654. The spectrum of source A is fit to a power-law model and the spectrum of 3FGL J1638.6–4654 is fit to a log-parabola model. Moreover, our timing analysis of source A uses photons in the energy range 0.2–300 GeV while 3FGL J1638.6–4654 is analyzed in the energy range 0.1–300 GeV. Our timing analysis would not be sensitive to flux variations (if any) below 0.2 GeV.

3.3. Spatial Distribution Analysis

We analyze the spatial distribution of source A, which is very likely to be associated with Kes 41, to examine whether it is a point-like or extended source. We apply both point-source and uniform-disk models with power-law spectra at the best-fit position to fit the emission in the energy range 2–300 GeV. In the point-source case, we set the spectral normalizations of the sources within 10° of Kes 41 as free parameters, and fix all of the other parameters at the 2FGL values. A TS value of 207 is obtained. In the disk case, the observed radius range for the uniform disks is 0.1″–0.5″ with a step of 0.1″. We fix all of the spectral parameters of the sources at the values obtained above, but allow the spectral normalization parameters of the disk models to be free parameters. The TSext value (calculated from 2 log(Ldisk/Lpoint)) for each radius is smaller than zero, while the extended source detection threshold is TSext = 16 (Lande et al. 2012), which implies that no significant extended emission is detected. As a result, the GeV γ-ray emission from source A seems to be point-like.

3.4. Spectral Analysis

The γ-ray spectrum of source A is extracted via the maximum likelihood analysis of the LAT data in 6 divided energy bands from 0.2–300 GeV (see Table 1). The spectral

\[ \chi^2 \text{ with 68 dof, and variability would be considered probable} \]

\[ \text{when TS}_{\text{var}} \text{ could exceed the threshold of 98.0 corresponding to 99\% confidence. The computed TS}_{\text{var}} \text{ of source A is 65.2, corresponding to a confidence level <50\% for a variable source. These results suggest that there is no significant long-term variability observed in the region of Source A in the 0.2–300 GeV energy range. On the other hand, we construct} \]

\[ \text{1000 s binned light curves of source A in the same energy range which are obtained through Fermi-LAT aperture photometry analyses10 using LAT photons within different aperture radius from 0.2′ to 0.5′. We analyze these light curves for periodic signals, but no significant periodicity is detected. However, this method is statistically limited and the periodicity is hard to detect due to the massive diffuse background photons in a low galactic latitude.} \]

\[ \text{There is a close positional correspondence between source A, suggested here as a steady source, and 3FGL J1638.6–4654, which is indicated as a variable source in the third Fermi-LAT Catalog (3FGL) (Acero et al. 2015). 3FGL J1638.6–4654 is detected in 0.1–300 GeV with a significance of 13σ and a 0.1–300 GeV energy flux ~7.3 × 10⁻¹¹ erg cm⁻² s⁻¹; source A has a higher significance (24σ) with an energy flux of ~7.5 × 10⁻¹¹ erg cm⁻² s⁻¹ in the 0.2–300 GeV energy range (see Section 4.1; the flux will be somewhat higher in 0.1–300 GeV). The use of different spectral models and different energy ranges in the two timing analyses may contribute to the discrepancy in the variability between source A and 3FGL J1638.6–4654. The spectrum of source A is fit to a power-law model and the spectrum of 3FGL J1638.6–4654 is fit to a log-parabola model. Moreover, our timing analysis of source A uses photons in the energy range 0.2–300 GeV while 3FGL J1638.6–4654 is analyzed in the energy range 0.1–300 GeV. Our timing analysis would not be sensitive to flux variations (if any) below 0.2 GeV.} \]

\[ \text{We analyze the spatial distribution of source A, which is very likely to be associated with Kes 41, to examine whether it is a point-like or extended source. We apply both point-source and uniform-disk models with power-law spectra at the best-fit position to fit the emission in the energy range 2–300 GeV. In the point-source case, we set the spectral normalizations of the sources within 10° of Kes 41 as free parameters, and fix all of the other parameters at the 2FGL values. A TS value of 207 is obtained. In the disk case, the observed radius range for the uniform disks is 0.1″–0.5″ with a step of 0.1″. We fix all of the spectral parameters of the sources at the values obtained above, but allow the spectral normalization parameters of the disk models to be free parameters. The TS}_{\text{ext}} \text{ value (calculated from 2 log(Ldisk/Lpoint)) for each radius is smaller than zero, while the extended source detection threshold is TS}_{\text{ext}} = 16 (Lande et al. 2012), which implies that no significant extended emission is detected. As a result, the GeV γ-ray emission from source A seems to be point-like.} \]

\[ \text{The γ-ray spectrum of source A is extracted via the maximum likelihood analysis of the LAT data in 6 divided energy bands from 0.2–300 GeV (see Table 1). The spectral} \]

\[ \text{\[ http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/aperture_photometry.html} \]

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\[ \text{Figure 2. Monthly γ-ray light curve of source A in the energy range of 0.2–300 GeV.} \]
normalization parameters of the sources within 5° of Kes 41 are allowed to vary, but all of the other source parameters are fixed. In addition to the statistical uncertainties associated with the likelihood fits to the data, the uncertainty of the Galactic diffuse background intensity is considered. We vary the normalization of the Galactic background by ±6% from the best-fit values at each energy bin and estimate the flux from the object of interest using these new artificially frozen values of the background, following the treatment in Abdo et al. (2009). The possible systematic errors are estimated to be 46% (0.2–0.5 GeV), 40% (0.5–1.0 GeV), 20% (1.0–3.0 GeV), and <15% (>3 GeV). We keep only those spectral flux points with TS higher than 4 (which corresponds to the detection significance of 2σ) and derive 95% flux upper limits in the other energy bins. The obtained spectral data for source A are provided in Table 1.

We fit the 0.2–300 GeV spectral data of source A with a power-law model. The obtained spectral shape is relatively flat with a photon index of Γ = 2.38 ± 0.03. The flux is (9.2 ± 1.0) × 10^{-11} erg cm^{-2} s^{-1}, corresponding to a luminosity of ~1.6 × 10^{36} d_{12}^2 erg s^{-1}, where d_{12} = d/12 kpc is the distance to the MC associated with SNR Kes 41 in units of the reference value estimated from the maser observation (Koralesky et al. 1998). See also Section 4.1 for an estimate of the flux and luminosity with an exponential cutoff.

### 4. DISCUSSION ON THE NATURE OF SOURCE A

Based on our analysis of 5.6 years of Fermi-LAT data for the environment surrounding Kes 41, we have found a γ-ray source detected at a significance of ~24σ that appears to be coincident with the northwest rim of Kes 41.

The relation between source A and Kes 41 is crucial for determining the origin of the γ-ray emission. In this section, we will discuss the possibility of the γ-ray emission arising from a pulsar and an SNR-MC hadronic interaction, respectively.

#### 4.1. A Pulsar?

Galactic pulsars are important γ-ray source candidates, and there have been numerous pulsars detected by Fermi-LAT in recent years (Abdo et al. 2010e). Although the 3σ error circle here does not include any known pulsars, the possibility of correspondence to a pulsar associated with Kes 41 still cannot be ignored. Theoretically, there may be a descendant stellar compact remnant after the core-collapse supernova (SN) explosion of the >18 M⊙ progenitor of the remnant (Zhang et al. 2015). Such a compact stellar remnant has not been conclusively associated with Kes 41 in the literature.

We fit the spectrum of source A with a power-law model with an exponential cutoff for a pulsar, dN/df = K E_{\gamma}^{-\alpha} \exp(-E_{\gamma}/E_{\gamma,\text{cut}}) typical for a pulsar (Abdo et al. 2010e). The model fit yields E_{\gamma,\text{cut}} = 4.0 ± 0.9 GeV and a spectral index of Γ = 1.9 ± 0.1. In this model, the flux in the energy range 0.2–300 GeV is (7.5 ± 0.9) × 10^{-11} erg cm^{-2} s^{-1}, and the corresponding luminosity is (1.3 ± 0.2) × 10^{36} d_{12}^2 erg s^{-1}. The significance of the exponential cutoff power law (approximately described by \sqrt{T}\text{S}_{\text{cutoff}} = \sqrt{T}\text{S}_{\text{PL}} - \text{cutoff} - T\text{S}_{\text{PL}} \Gamma) is ~6σ. The spectral shape of source A is similar to those of the detected γ-ray pulsars (Abdo et al. 2013), which usually show flat spectra below 1 GeV and exponential cutoffs in the energy range ~0.4–6 GeV. If this source is a “kicked” pulsar moving from the SNR center, then the best-fit position, offset away, would imply a projected traverse velocity of ~80–900 km s^{-1} if the remnant’s age estimate 4–110 kyr (Zhang et al. 2015) is adopted. (The closer the position within the 3σ circle to the SNR center, the lower the velocity would be.) The upper limit of the velocity seems very high, but there is also growing evidence for high pulsar velocities, even exceeding 4 × 10^{3} km s^{-1} (e.g., PSR B2011+38 and PSR B1718–35; Zou et al. 2005). On the other hand, if it is an associated pulsar at ~12 kpc, then its γ-ray luminosity of the order of 10^{36} erg s^{-1} (Section 3.4) would be among the highest among (radio loud) γ-ray pulsars (Abdo et al. 2013), which seems difficult to accept in view of the no detection of any radio pulse here.

#### 4.2. Emission from Particles Accelerated by Kes 41?

The 3σ error circle is on the northern boundary of SNR Kes 41 and essentially consistent with the shock-MC interaction region. Actually, it covers not only the 1720 MHz OH maser but also the northwestern molecular gas at a systemic velocity of V_{LSR} ~ -50 km s^{-1} that surrounds the remnant (Zhang et al. 2015; see Figure 3). It is very possible that the γ-ray emission arises from relativistic particles accelerated by the SNR shock waves. We need to confront the leptonic and hadronic mechanisms with the obtained γ-ray data.

##### 4.2.1. Leptonic Scenario

First, we consider the scenario in which the γ-ray emission comes from inverse Compton scattering off the relativistic electrons accelerated by the SNR shock. The emissivity of the bremsstrahlung process is compatible with that of the p–p process if the number ratio of electrons to protons at a given energy, K_{ep}, is of the order of ~0.1 (Gaissier et al. 1998). Nevertheless, the values of K_{ep} observed at Earth (Yuan et al. 2012) and predicted by the diffusive shock acceleration theory (Bell 1978) are both of the order of ~0.01. Therefore, the bremsstrahlung γ-ray is usually insignificant.

We fit a power-law electron spectrum with a cutoff, dN_e/dE_e \propto E_e^{-\alpha_e} \exp(-E_e/E_{e,\text{cut}}), to the spectral data and only consider the cosmic microwave background as the seed photons (referred to as Case A). As can be seen in Figure 4 (blue dotted line), the fitting effect is less satisfactory. We obtain \alpha_e \approx 2.0 and E_{e,\text{cut}} \approx 400 GeV (also see Table 2). The normalization is given by the total energy deposited in

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Table 1: Fermi LAT Flux Measurements of Source A in the Kes 41 Region

| E_{\gamma} (Energy Band) (GeV) | E_{\gamma}^\Delta dN/(E_{\gamma}/dp_{\gamma}) | E_{\gamma}^\Delta dN/(E_{\gamma}/dp_{\gamma}) | TS Value |
|-------------------------------|--------------------------------|--------------------------------|-------------|
| 0.32 (0.20–0.50)             | 15.9 ± 3.3 ± 7.3               | 0.1 ± 0.3 ± 0.1               | 9            |
| 0.71 (0.50–1.00)             | 24.4 ± 4.6 ± 9.9               | 0.6 ± 0.9 ± 1.8               | 113          |
| 1.73 (1.00–3.00)             | 21.3 ± 1.8 ± 4.6               | 0.4 ± 0.3 ± 0.3               | 224          |
| 5.48 (3.00–10.0)             | 10.7 ± 1.2 ± 1.7               | 0 ± 0.1 ± 0.1                | 105          |
| 17.3 (10.0–30.0)             | 2.4 ± 1.0 ± 0.3                | 0 ± 0.1 ± 0.1                | 2 ± 0.1      |
| 94.9 (30.0–300)              | <2.9^\alpha                  | <2.9^\alpha                  | 2 ± 0.1      |

Notes.

- The first column of errors lists statistical errors and the second lists systematic errors.
- The 95% upper limit.
electrons with energy above 1 GeV, \( W_p(>1 \text{ GeV}) \sim 1.3 \times 10^{51} \text{ erg} \). This electron energy budget is unreasonably high as the order of the canonical SN explosion energy.

### Table 2

| \( \alpha_p \) | \( \Delta \sigma_p \) | \( E_p \) (GeV) | \( n_i E_0^2 W_p(>1 \text{ GeV}) \) (10^{51} \text{ erg cm}^{-3}) |
|----------------|----------------|----------------|--------------------------------------------------|
| **Case A**      | 2.0            | 0.7            | 18.7                                            |
| \( t_{age} \) (kyr) | 10             | 0.7            | 40.4                                            |
| **Case B**      | 2.0            | 1.2            | 18                                               |
| \( t_{age} \) (kyr) | 10             | 0.7            | 11                                               |
| **Case C**      | 4              | 2.4            | 5                                               |
| \( t_{age} \) (kyr) | 10             | 0.7            | 11                                               |
| **Case D**      | 10             | 2.4            | 18                                              |
| \( t_{age} \) (kyr) | 100            | 2.4            | 40                                              |

4.2.2. Hadronic Scenario

Next, we consider the scenario in which the \( \gamma \)-ray emission is produced by the collision of the shock accelerated protons with dense molecular gas. For the case (referred to as **Case B**) in which the protons collide with the dense target molecular gas (with average number density \( n_i \)), we assume for the protons a broken power-law distribution, \( dN_p/dE_p \propto E_p^{-\alpha_p} \left(1 + (E_p/E_0)^2\right)^{-\Delta \sigma_p/2} \), to fit the spectral data (see Figure 4 (red dashed line) and Table 2). We thus obtain \( \alpha_p = 2.0, \Delta \sigma_p = 1.2 \), and a break energy of \( E_0 = 18 \text{ GeV} \). The total energy deposited in the protons with energy above 1 GeV is \( W_p(>1 \text{ GeV}) \sim 0.7 \times 10^{50} E_{51}(n_i/100 \text{ cm}^{-3})^{-1} \text{ erg} \), where \( E_{51} = E_{SN}/10^{51} \text{ erg} \) is the dimensionless SN explosion energy. SNR Kes 41 has been found to be surrounded by molecular gas with density \( n_H \sim 140–500 \text{ cm}^{-3} \) in the northwest and HI gas with density \( n(HI) \sim 40 \text{ cm}^{-3} \) in the southeast (also see Figure 3). If the mean target density \( n_i \) is approximately of the order of 100 cm\(^{-3}\), then \( W_p(>1 \text{ GeV}) \sim 1 \times 10^{50} E_{41} \text{ erg} \), namely, the fraction, \( \eta \), of the SN explosion energy converted to protons is of the typical order of 0.1. While in this scenario the hadronic \( \gamma \)-rays are emitted at the SNR shock, it is noteworthy that the centroid of the 3\( \sigma \) circle of source A appears to be outside the northwestern boundary of the SNR.

The hadronic emission can alternatively be considered as originating from adjacent MCs “illuminated” by the diffusive relativistic protons escaping from the SNR shock front. In the finite volume of a nearby cloud, the protons’ energy distribution can be obtained by calculating the diffusive escaping protons accumulatively throughout the history of the SNR expansion (**Case C**). For such a calculation, in the following, we refer to Li & Chen (2012) and the references therein for details of the model.

In the model calculation, we assume a converted CR proton energy fraction of \( \eta = 0.1 \) and an SN explosion energy of \( E_{SN} = 10^{51} \text{ erg} \). The SNR radius in the southeast–northwest orientation is adopted as \( R_s \approx 11 \text{ pc} \). The \( \gamma \)-rays are assumed to arise from an MC of thickness \( \Delta R \), that is in contact with the shock front; therefore, the MC center is \( R_c = R_s + \Delta R/2 \) away from the SNR center. According to Zhang et al. (2015), the SNR evolves in a cavity and may have drastically

Figure 3. Tri-color image of Kes 41 in multiwavelengths. Red: Fermi-LAT 2–300 GeV counts map centered at SNR Kes 41, smoothed with a Gaussian of width 0.6 (per pixel bin representing 0:01). Blue: {\(^1\)CO (J = 1–0) integrated emission (\( V_{LSR} = -70 \) to \(-40 \text{ km s}^{-1}\)) with a field of view of 11’ \( \times \) 10’.

Green: HI emission line from SGPS integrated map (\( V_{LSR} = -55 \) to \(-50 \text{ km s}^{-1}\)). The green contours and the green and cyan crosses are the same as in Figure 1. The white curves show the TS = 100, 144, and 196 contours (which correspond to significance 10\( \sigma \), 12\( \sigma \), and 14\( \sigma \), respectively). The white diamond indicates the location of the 1720 MHz OH maser (Koralesky et al. 1998) and the green circles label the positions of known pulsars. The dashed blue circle indicates the 3\( \sigma \) error circle of the best-fit position of source A.

Figure 4. Fermi \( \gamma \)-ray spectral energy distribution of source A fit with various models (see text). Systematic errors (see Section 3.4) are indicated by black bars and the statistical errors are indicated by red bars.
decelerated and entered the radiative phase as soon as the blast wave encountered the cavity wall, after a Sedov evolution lifetime (Sedov 1959) of \( t_{\text{esc}} = 4 \times 10^3 (n_1/0.3 \, \text{cm}^{-3}/E_5)^{1/2} (R_s/11 \, \text{pc})^{3/2} \) years. We assume that the particle acceleration process is not significant after this time. Therefore, the average distribution of the cumulative escaping protons in the volume of the MC at the remnant age \( t_{\text{age}} \) is rewritten as

\[
F_{\text{ave}}(E_p, t_{\text{age}}) = \int_{R_s - \Delta R_s/2}^{R_s + \Delta R_s/2} r^2 dr \int_0^{2\pi} \int_0^\pi \int_{t_{\text{age}} - t_i}^{t_{\text{age}}} f(E_p, R_{\text{bet}}(R_s, t_i, \theta, \phi), t_{\text{diff}}) R_s^2 (t_i) \sin \theta \, d\theta \, d\phi \, dt_i \int_{R_s - \Delta R_s/2}^{R_s + \Delta R_s/2} r^2 dr,
\]

(1)

where \( t_i \) is the time at which a proton escapes from the SNR shock, \( t_{\text{diff}} = t_{\text{age}} - t_i \) is the diffusion time after escape, \( R_{\text{bet}} \) is the distance between the escape point on the shock surface and a given point in the cloud (with position angles \((\theta, \phi)\)), and \( f(E_p, R_{\text{bet}}(R_s, t_i, \theta, \phi), t_{\text{diff}}) \) is the distribution function at a given point of the protons that escape from the unit area at an arbitrary escape point. Considering the remnant’s age range \( \sim 4-100 \) kyr estimated from the ionization timescale of the X-ray emitting gas (Zhang et al. 2015), we calculate the model with three age numbers, 4, 10, and 100 kyr. This model can fit the spectral points as well, as exemplified by the solid line for \( t_{\text{age}} = 10 \) kyr in Figure 4. The model parameters are listed in Table 2. The photon index \( \alpha_p = 2.4 \), the energy-dependent index of the diffusion coefficient \( \delta = 0.7 \) and the correction factor of slow diffusion around the SNR \( \chi \sim 0.01-0.1 \) are in normal ranges. The \( \Delta R_s \) value \( \sim 5-13 \) pc \((\sim 0-02-06)\) implies that the MC involved in the \( p-p \) hadronic interaction is essentially within the \( 3\sigma \) circle of source A. Note that such a source size is much smaller than the PSF size \( \sim 0.5 \) of the Fermi-LAT at energies above \( 2 \) GeV, consistent with the above judgement of a point-like source. The “illuminated” MC mass \( M_{36} \), around \( 10^{5} M_\odot \), seems reasonable compared with the mass of the molecular gas “reservoir” in the northwest, which is no less than \( \sim \) a few times \( 10^{5} M_\odot \), estimated from a limited field of view of the CO observation (Zhang et al. 2015).

However, the cavity wall may send a reflected shock backward when the blast wave collides with it (Zhang et al. 2015). If the reflected shock can still effectively accelerate particles after the forward shock becomes radiative, then the situation would be more complicated than the above cases. For simplicity, we approximate this case as a continuous proton injection from the SNR center (Aharonian & Atoyan 1996; Case D). In this case, the MC is regarded as a point at \( R_s \) from the SNR center and the same energy conversion fraction \( \eta = 0.1 \) is adopted. We follow the algorithm described in Aharonian & Atoyan (1996) and fit the spectral data, as exemplified by the green dashed line for \( t_{\text{age}} = 10 \) kyr and \( R_s = 20 \) pc in Figure 4. These model results are generally similar to those of Case C, with a slightly harder model spectrum at \( \geq 100 \) GeV. For the three sets of parameters with \( t_{\text{age}} = 10 \) and 100 kyr, we again have \( \alpha_p = 2.4 \) and \( \delta = 0.7 \).

The \( \chi \) values are \( \sim 0.05-0.5 \) in a normal range. A higher mass of the “illuminated” part of MC than Case C is required, but is still consistent with the MC mass estimate from the CO observation in the order of magnitude.

The hadronic scenarios, both the interaction at the shock (Case B) and the illumination by escaping protons (Case C/D), can generally explain the \( \gamma \)-ray properties of source A. The escape cases have higher model spectra at \( \geq 10 \) GeV than the interaction-at-the-shock case. Further TeV observations will likely be of help to distinguish the two scenarios.

5. COMPARISON WITH OTHER GeV-DETECTED SNRs IN MC ENVIRONMENTS

We now present a brief discussion of Kes 41 within the context of other Galactic SNRs that have been detected at \( \gamma \)-ray energies. An intriguing trend has emerged in these studies where Galactic SNRs that are known to be interacting with dense clouds and that are detected at (very) high energies also appear to exhibit contrasting morphologies in the X-ray and radio. Specifically, these sources exhibit the shell-like radio morphologies that are characteristic of SNRs coupled with a center-filled X-ray morphology that is thermal in origin, and therefore belong to the class of thermal composite or mixed-morphology SNRs (also see Section 1). Actually, about half of the 36–37 known thermal composites have been found to be interacting with adjacent MCs (see Table 4 in Zhang et al. 2015). While the origin of these contrasting morphologies remains uncertain, it appears that the interaction between the SNRs and the dense clouds plays a crucial role. Proposed origins for these morphologies include the evaporation of shock-engulfed cloudlets, thermal conduction within the interior hot gas, and heating by the shock reflected from the wind-cavity wall; the reader is referred to Chen et al. (2008) and references therein for a detailed review of these proposed mechanisms.

We tabulate the thermal composite SNRs that have been detected at \( \gamma \)-ray energies by Fermi-LAT in Table 3. So far, there are 13 SNRs (including Kes 41) of this class that have associated GeV \( \gamma \)-ray emission, and an additional six of them possibly have associated GeV \( \gamma \)-ray emission, as listed in Table 3. We can see that most of the GeV-detected thermal composites are in physical interaction with MCs.

In Table 3, we collect the photon indices in the GeV band and adopt the luminosities in, or convert them to, the 1–100 GeV energy range for ease of comparison. The \( \sim \)GeV spectra of these SNRs are soft, with power-law photon indices of \( \Gamma \gtrsim 2.0 \), in distinct contrast with the hard spectra (\( \Gamma \sim 1.4-1.8 \)) of the supposed leptonic process dominated \( \gamma \)-ray SNRs, e.g., RX J0852.0–4622 (Tanaka et al. 2011 and RCW 86; Yuan et al. 2014). Except for HB 21 and Kes 27, the 1–100 GeV luminosities of the 13 identified GeV \( \gamma \)-ray sources are on the order of a few times \( 10^{35} \) erg s\(^{-1} \), which are significantly higher than those of the leptonic process dominated SNRs (e.g., <\( 10^{34} \) erg s\(^{-1} \) for RX J0852.0–4622; Tanaka et al. 2011 and RCW 86; Yuan et al. 2014). For the exceptional cases of HB 21 and Kes 27, the low luminosities may be due to proton collisions with only a very small amount of dense clouds (e.g., Pivato et al. 2013; Xing et al. 2015). We note that where detailed modeling has been applied to the \( \gamma \)-ray spectra of these sources, hadronic models have generally proved to give better fits to the data than leptonic models (except for the uncertain cases of Kes 17 and HB 9).

These past \( \gamma \)-ray observations of thermal composite SNRs—including the observation of Kes 41 that is presented in this
paper—have thus produced insights into how SNRs interact with MC and how SNRs accelerate CR particles. Additional γ-ray observations of thermal composites are necessary and timely to explore the relation between emission at these high energies and the origin of the contrasting morphologies that characterize SNRs of this type.

6. SUMMARY

We perform an analysis of the γ-ray emission in a 14° × 14° region centered on the thermal composite SNR Kes 41, using 5.6 years of Fermi-LAT observation data. We find a point-like source to the northwest of the SNR with a significance of 24σ in 0.2–300 GeV. Neither significant long-term variability nor periodicity is detected from the timing analysis of source A in the same energy range. The 3σ error circle, 0.09 in radius, covers the 1720 MHz OH maser and is essentially consistent with the location of the V$_{SR}$ ~ 50 km s$^{-1}$ MC with which the SNR interacts. The source emission can be described by a power-law spectrum with an exponential cutoff with a photon index of 1.9 ± 0.1 and a cutoff energy of 4.0 ± 0.9 GeV. The corresponding 0.2–300 GeV flux is (7.5 ± 0.9) × 10$^{-11}$ erg cm$^{-2}$ s$^{-1}$, and the luminosity is ~1.3 × 10$^{36}$ erg s$^{-1}$ at a distance of 12 kpc. Although the spectrum is similar to those of pulsars, there is no radio pulsar in the 3σ circle responsible for the high luminosity. While the power-law electron spectrum with a cutoff for inverse Compton scattering would lead to difficulty in the electron energy budget, the emission can be naturally explained by the hadronic interaction between the relativistic protons accelerated by the shock of SNR Kes 41 and the adjacent northwestern MC. By comparison with the hadronic interaction at the shock, which appears off the best-fit position of the source, illumination of the adjacent MC by the protons escaping from the shock front seems more consistent with observations. A list of Galactic thermal composite SNRs detected at GeV γ-ray energies by Fermi-LAT is presented in this paper.

B.L. is grateful to Xia Fang, Ning-Xiao Zhang, and Zheng-Gao Xiong for help with Fermi data analysis. We thank the support of NSFC grants 11233001 and 11403075. This work has also benefited from 973 Program grant 2015CB857100, grant 20120901110048 from the Educational Ministry of China, and the grants from the 985 Project of NJU and the Advanced Discipline Construction Project of Jiangsu Province. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

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Table 3

Parameters of the γ-ray Emission of the Galactic Thermal Composite SNRs Obtained from Fermi-LAT Observation

| Source                   | Distance (kpc) | Γ             | $I_{\gamma, 100 GeV}$ (10$^{35}$ erg s$^{-1}$) | MC Interaction | References |
|--------------------------|---------------|---------------|---------------------------------------------|----------------|------------|
| G6.4–0.1 (W28)           | 2.0           | 2.74 ± 0.06$^b$ | 1.0                                         | Y              | (1), (2)   |
| G31.9+0.0 (3C 291)        | 7.2           | 2.50 ± 0.04$^b$ | 4.0                                         | Y              | (3), (4)   |
| G34.7–0.4 (W44)          | 2.8           | 3.02 ± 0.10$^b$ | 2.7                                         | Y              | (5), (6)   |
| G43.3–0.2 (W49B)         | 8             | 2.29 ± 0.02$^c$ | 8.0                                         | Y              | (7), (8)   |
| G49.2–0.7 (W51C)         | 6             | 2.5 ± 0.1$^b$  | 4.4                                         | Y              | (9), (10)  |
| G89.0+4.7 (HB 21)        | 1.7           | 2.33 ± 0.03$^c$ | 0.13                                        | Y              | (11), (12) |
| G189.1+3.0 (IC 443)      | 1.5           | 2.61 ± 0.04$^b$ | 1.0                                         | Y              | (5), (13)  |
| G304.6+0.1 (Kes 17)      | 9.7           | 2.0 ± 0.3$^c$  | 12                                          | Y              | (14), (15) |
| G327.4+0.4 (Kes 27)      | 4.3           | 2.5 ± 0.1$^c$  | 0.24                                        | ...            | (16), (17) |
| G337.8+0.1 (Kes 41)      | 12            | 2.38 ± 0.03$^c$ | 7.7                                         | Y              | (18)       |
| G348.5+0.1 (CTB 37A)     | 11.3          | 2.19 ± 0.07$^c$ | 7.8                                         | Y              | (19), (20), (21) |
| G357.7–0.1 (MSH 17-39)   | 12            | 2.5 ± 0.3$^c$  | 5.8                                         | Y              | (22), (23) |
| G359.1–0.5               | 7.6           | 2.60 ± 0.05$^c$ | 4.0                                         | Y              | (24), (25) |
| G0.0+0.0 (Sgr A East) (?)$^d$ | 8.0          | 2.32 ± 0.03$^c$ | 8.7                                         | Y              | (26), (23) |
| G132.7+1.3 (HB 3) (?)$^d$ | 2.2           | 2.30 ± 0.11$^c$ | 0.04                                        | Y$^?$          | (27), (23) |
| G156.2+5.7 (?)$^d$       | 3             | 2.35 ± 0.09$^c$ | 0.26                                        | ...            | (28), (23) |
| G290.1–0.8 (MSH 11-61A) (?)$^d$ | 7           | ~2.28$^c$    | 1.5                                         | ?              | (22), (23) |
| G160.9+2.6 (HB 9) (?)$^e$ | 1.0           | 2.30 ± 0.05$^c$ | 0.013                                       | ?              | (29)       |
| G166.0+4.3 (?)$^e$       | 4.5           | 2.27 ± 0.1$^c$  | 0.11                                        | ?              | (30), (31) |

Notes.

$^a$ Adopted from Jang et al. (2010) SNR-MC association table.
$^b$ The photon index above the break energy for broken power-law spectrum.
$^c$ The photon index of a single power-law spectrum.
$^d$ Question mark: the association of the detected γ-ray emission with the SNR is uncertain.
$^e$ Question mark: not listed in the latest 3FGL catalog (Acero et al. 2015).

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