DISCOVERY OF GAMMA-RAY EMISSION FROM THE SUPERNOVA REMNANT Kes 17 WITH FERMI LARGE AREA TELESCOPE

J. H. K. Wu1, E. M. H. Wu1, C. Y. Hu1, P. H. T. Tam3, R. H. H. Huang3, A. K. H. Kong3,4, and K. S. Cheng1

1 Department of Physics, University of Hong Kong, Pokfulam Road, Hong Kong
2 Department of Astronomy and Space Science, Chonnam National University, Daejeon 305-764, Republic of Korea; cyhui@cnu.ac.kr
3 Institute of Astronomy and Department of Physics, National Tsing Hua University, Hsinchu, Taiwan

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ABSTRACT

We report the discovery of GeV emission at the position of supernova remnant Kes 17 by using the data from the Large Area Telescope on board the Fermi Gamma-ray Space Telescope. Kes 17 can be clearly detected with a significance of $\sim 12\sigma$ in the 1–20 GeV range. Moreover, a number of $\gamma$-ray sources were detected in its vicinity. The $\gamma$-ray spectrum of Kes 17 can be described well by a simple power law with a photon index of $\Gamma \sim 2.4$. Together with the multiwavelength evidence for its interactions with the nearby molecular cloud, the $\gamma$-ray detection suggests that Kes 17 is a candidate acceleration site for cosmic rays.

Key words: acceleration of particles – cosmic rays – gamma rays: ISM – ISM: individual objects (Kes 17)

Online-only material: color figures

1. INTRODUCTION

For more than 70 years, it has been suggested that supernova remnants (SNRs) are promising sites for accelerating Galactic cosmic rays (GCRs) (Baade & Zwicky 1934). It has been well established that relativistic leptons were produced in shell-type SNRs and give rise to the observed non-thermal X-rays (cf. Weisskopf & Hughes 2006). These leptons are typically accelerated to energies $\lesssim 100$ TeV (e.g., Reynolds & Keohane 1999; Hendrick & Reynolds 2001; Eriksen et al. 2011). However, they are not sufficient to account for the energetics as well as the composition of observed GCRs, which contain a considerable fraction of hadrons (i.e., proton and heavy ions) up to the knee of their spectra (i.e., $\sim 10^{15}$ eV; cf. Sinnis et al. 2009).

The joint radio/X-ray observations of the remnant SN 1006 suggest the presence of a concaved spectrum of synchrotron-emitting electrons, which is expected from the modification of the shock dynamics by the pressure of the accelerated protons (Allen et al. 2008). The efficient acceleration of hadronic cosmic rays (CRs) in SN 1006 is also supported by the magnetic field amplification in some thin X-ray filaments, which has presumably resulted from the nonlinear back-reaction of CRs (Berezhko et al. 2003). The observed X-ray variability of the small-scale structures in the young SNR RX J1713.7-3946 also implies that the magnetic fields have been amplified to the order of a milligauss, which provides the key condition for accelerating protons to energies $>100$ TeV (Uchiyama et al. 2007).

X-ray observation of another historical remnant, Tycho’s SNR, has revealed that the ratio of the separation between the forward shock and the contact discontinuity is smaller than expected from the adiabatic evolution, which can be explained by the efficient acceleration of ions at the forward shock (Warren et al. 2005). Further evidence for the hadronic acceleration in Tycho’s SNR has been revealed by a deep Chandra observation (Eriksen et al. 2011). The spacing of the non-thermal X-ray strips is consistent with the Larmor radii of $\sim 10^{14–15}$ eV protons in the remnant (see Figure 2 in Eriksen et al. 2011).

Since relativistic protons do not radiate efficiently, X-ray observation can only infer their presence indirectly. On the other hand, $\gamma$-rays are generally accepted as the smoking gun of CR acceleration due to the decay of neutral pions $\pi^0$ produced in the collision of the accelerated hadrons. Therefore, increasing support for SNRs as acceleration sites has been found by $\gamma$-ray observations in recent years.

Thanks to the ground-based observatories, such as H.E.S.S., 17 SNRs have so far been detected in the TeV regime (see Caprioli 2011 for a recent review). While these observations provided solid evidence for the presence of energetic particles, as it is difficult to disentangle various possible components $(\pi^0$-decay, bremsstrahlung, and/or inverse Compton due to electrons) in the TeV band, the debate on whether the origin of this high-energy emission is hadronic or leptonic remains.

The spectrum between $\sim 100$ MeV to few tens of GeV has been expected to be rather different between hadronic/leptonic models (Slane 2007). Therefore, the Large Area Telescope (LAT) on board the Fermi Gamma-ray Space Telescope, which has optimal sensitivity in this energy range, provides a promising key to settle the debate. So far, 13 SNRs have already been detected by LAT (cf. Table 1 in Caprioli 2011 and references therein). A number of investigations do favor the scenario of $\pi^0$-decay (e.g., Abdo et al. 2009, 2010a). On the other hand, leptonic emission is dominant in some cases (e.g., Abdo et al. 2011).

In order to constrain the proportion of SNRs with hadronic/leptonic $\gamma$-ray emission in our Milky Way, the sample size of $\gamma$-ray bright SNRs needs to be enlarged. In view of this, we initiate a census of Galactic SNRs with LAT. In order to enhance detectability, we particularly focus on those SNRs that have interactions with molecular clouds (MCs) for the initial stage of this campaign (cf. Jiang et al. 2010). Among these candidates, Kes 17 is one of the poorly studied remnants.

Kes 17 (G304.6+0.1) was first detected in the radio band by Shaver & Goss (1970). A lower bound of 9.7 kpc was placed on its distance by hydrogen line interferometric study (Caswell et al. 1975). Follow-up radio observations have revealed an...
irregular shell morphology which was suggested as a result of the collision of the SNR shock front and its dense environment (Möllenhoff et al. 1985; Whiteoak & Green 1996). This scenario was supported by the detection of a 1720 MHz OH maser in its direction (Fray et al. 1996). In an infrared survey of SNRs in the inner region of Milky Way, Kes 17 was detected with the support of the detection of a 1720 MHz OH maser in its vicinity (Reach et al. 2006). Along a subsequent infrared spectroscopic observation by Spitzer and Akari, evidence for the shocked MC was suggested (Hewitt et al. 2009; Lee et al. 2011). Very recently, the thermal X-ray plasma and a small non-thermal contribution have been detected by XMM-Newton (Combi et al. 2010). The X-ray properties indicate that Kes 17 is a middle-aged SNR (2.8–6.4) × 10^4 yr old. On the other hand, no TeV emission has been uncovered yet. In this Letter, we report the detection of GeV emission from Kes 17 with LAT in ~30 months of data.

2. DATA ANALYSIS AND RESULTS

In this analysis, we used the LAT data between 2008 August 4 and 2011 January 31. To reduce and analyze the data, the Fermi Science Tools v9r18p6 package, available from the Fermi Science Support Center, was used. We restricted the events in the “diffuse” class (i.e., class 3 and class 4) only. In addition, we excluded the events with zenith angles larger than 105° to reduce the contamination by Earth albedo gamma rays.

Events were selected within a circular region of interest (ROI) centered at the nominal position of Kes 17 (i.e., R.A. = 13^h 05^m 59^s, decl. = -62° 42' 18") and extending to a radius of 10°, to reduce systematic uncertainties due to inaccurate background subtraction in this complex region. A binned photon count map in 0.1–100 GeV was first produced with the task gtbin for a preliminary visual inspection (Figure 1). A γ-ray excess can be clearly identified at the nominal position of Kes 17 even before subtracting intense background. We note that two sources in the first Fermi/LAT catalog (1FGL), 1FGL J1309.9-6229c and 1FGL J1301.4-6245c, are located in the vicinity of Kes 17 (Abdo et al. 2010b). Nevertheless, there is no obvious excess at the positions of these two sources in Figure 1. On the other hand, γ-ray emission at the eastern side and the southwestern side of the central bright feature can be seen in Figure 1.

Interestingly, the southwestern excess is close to an unidentified TeV source HESS J1303-631. The orientation and the extent of HESS J1303-631 are illustrated by the dashed elliptical region in Figure 1. Based on the fact that the observed TeV flux is only a few percent of the spin-down flux of PSR J1301-6305 and the pulsar is located at the peak of the extended TeV emission, it has been suggested that HESS J1303-631 can be the pulsar wind nebula associated with PSR J1301-6305, though this has not yet been confirmed unambiguously (Aharonian et al. 2005a). Other speculations on the nature of this TeV object like γ-ray burst remnant (Atoyan et al. 2006) and dark matter accumulations (Ripken et al. 2008) have also been proposed. Utilizing SIMBAD, we have also identified the infrared source IRAS 13010-6254 close to the peak of the southwestern excess.

Before we proceeded to analyze the emission nature of Kes 17, we first checked the consistency between the properties of these two nearby sources as reported in 1FGL and those inferred in our data by performing an unbinned likelihood analysis in 0.1–100 GeV, which is the energy band adopted in 1FGL. For the background subtraction, we included the Galactic diffuse model (gll_iem_v02.fit), the isotropic background (isotropic_iem_v02.txt), as well as all point sources in 1FGL within 10° from the center of the ROI (total of 28 sources). All these 1FGL sources were assumed to be point sources which have a simple power-law (PL) spectrum. While the spectral parameters of the 1FGL sources located within the ROI were set to be free, we kept the parameters for those lying outside our adopted region fixed at the values given in 1FGL (Abdo et al. 2010b). We also allowed the normalizations of diffuse background components to be free.

Without considering the contribution from Kes 17, the photon indices and the fluxes of these two sources are consistent with those reported in 1FGL. Both sources can be detected at a significance of ~15σ in the ~30 month data. We then proceeded to reexamine the emission properties of these sources, and we performed a detailed spectral analysis with Kes 17 included in the model.

In order to minimize the contamination due to point-spread function wings of surrounding sources, we restricted all the subsequent analysis in 1–20 GeV for obtaining robust results. We first assumed a PL spectrum of Kes 17 for an unbinned likelihood analysis with the aid of the task gtlike, the best-fit model yields a photon index of Γ = 2.42 ± 0.16, a prefactor of (1.80 ± 1.05) × 10^{-3} cm^{-2} s^{-1} MeV^{-1}, and a test-statistic (TS) value of 146 which corresponds to a significance of 12σ. Its photon flux in this band is (4.7 ± 0.7) × 10^{-11} erg cm^{-2} s^{-1}. The corresponding integrated energy flux is f_{\gamma} = 1.9^{+3.4}_{-1.5} × 10^{-11} erg cm^{-2} s^{-1}. With the full energy range of 1–20 GeV divided into five logarithmically equally spaced energy bins, the binned spectrum is constructed from the independent fits of each

\footnote{The quoted errors of the energy flux have taken the statistical uncertainties of both photon index and prefactor into account.}
Figure 2. Fermi-LAT spectrum of Kes 17. The full energy range 1–20 GeV is divided into five energy bins. The data points and the vertical error bars correspond to independent fits in the respective bins. The solid line represents the best-fit power-law model inferred in the full energy band (i.e., $\Gamma = 2.42$).

Figures and tables are not included in this text. The text continues as follows:

bin, which is displayed in Figure 2. Besides a simple PL model, we have also examined whether an exponential cutoff power-law (PLE) or a broken power-law (BKPL) can improve the fit. The fittings with PLE and BKPL yield the TS values of 146 and 145, respectively. Based on the likelihood ratio test, the additional spectral parameters in PLE/BKPL are not statistically required for describing the observed $\gamma$-ray spectrum. Hence, we will not discuss these models any further in this work.

In 1–20 GeV and with the contribution from Kes 17 included, the photon indices (photon flux) of 1FGL J1309.9-6229c and 1FGL J1301.4-6245c are $\Gamma = 2.32 \pm 0.18\,(3.6 \pm 0.6) \times 10^{-9}\,\text{cm}^{-2}\,\text{s}^{-1}$ and $\Gamma = 2.63 \pm 0.18\,(3.7 \pm 0.6) \times 10^{-9}\,\text{cm}^{-2}\,\text{s}^{-1}$, respectively. Their significances are lowered to $\sim 9\sigma$ and $\sim 8\sigma$, respectively.

We have computed the $2' \times 2'$ TS map in 1–20 GeV centered at the nominal position of Kes 17 by using gtksmap. This is shown in Figure 3. With the aid of gfindsrc, we determined the best-fit position in 1–20 GeV to be R.A. = 13$^h$05$^m$55$^s$01, decl. = $-62^\circ39'49''7$ (J2000) with a 1$\sigma$ error radius (statistical) of 0$''$042, which is illustrated with a black circle in Figure 3. Apart from the bright central source, two additional features are noted in the TS map. One feature is apparently extended to the southwest from Kes 17 (referred to as Source SW hereafter). The other feature located on the eastern side appears to be a distinct source (referred to as Source E hereafter). The emission of Sources SW and E is peaked at R.A. = 13$^h$04$^m$11$^s$00, decl. = $-63^\circ14'52''9$ (J2000) and R.A. = 13$^h$10$^m$39$^s$0, decl. = $-62^\circ47'08''7$ (J2000), which is separated from the nominal remnant center of Kes 17 at 0$''$58 and 0$''$54, respectively.

To examine the spectral properties and significance of these features, we assumed a PL spectrum and a point source model at their peak positions. With Sources SW and E included in the source model, we have re-performed the unbinned likelihood analysis. We summarize the properties of Kes 17 as well as the nearby source in Table 1.

### Table 1

| Source  | $\Gamma$   | $f_\gamma$ (1–20 GeV) | TS  |
|---------|-------------|-----------------------|-----|
| Kes 17  | 2.33 ± 0.18 | 3.92 ± 0.67           | 121 |
| SW      | 2.57 ± 0.23 | 3.02 ± 0.59           | 60  |
| E       | 1.87 ± 0.32 | 1.69 ± 0.60           | 57  |
| 1FGL J1309.9-6229c | 2.39 ± 0.22  | 2.86 ± 0.67           | 53  |
| 1FGL J1301.4-6245c | 2.55 ± 0.20  | 3.11 ± 0.61           | 53  |

**3. DISCUSSION**

In this Letter, we report the discovery of the GeV emission from the SNR Kes 17. The remnant can be detected at a significance of $\sim 12\sigma$ in 1–20 GeV. The $\gamma$-ray spectrum can be modeled by a single PL with a photon index of $\Gamma \sim 2.4$.

We have also found various $\gamma$-ray sources in the vicinity of Kes 17 (cf. Table 1 and Figure 3). It is quite difficult to confirm whether they have actual physical connections because Kes 17 is one of most poorly studied SNRs. However we can compare them to Kes 17 and W28 can enable us to study how the CRs are released in SNRs as well as their propagation in the interstellar medium (ISM; Li & Chen 2010).

It is instructive to compare the spatial separation between Source SW and Kes 17 with the CR diffusion. Assuming the diffusion coefficient of the CRs in the ISM as $D_{\text{ISM}} \approx$...
$10^{28} \text{(pc/10 GeV)}^{0.5} \text{cm}^2 \text{s}^{-1}$, where $p$ is the CR momentum (cf. Ohira et al. 2011; Berezinskii et al. 1990). Adopting the remnant age of $t_{\text{SNR}} \sim 5 \times 10^4$ yr (Combi et al. 2010), the diffusion scale is estimated as $l_{\text{CR}} \sim \sqrt{D t_{\text{SNR}}} \sim 40$ pc for the CRs with energies of $\sim 10$ GeV. At the distance of 9.7 kpc, this translates into an angular separation of $\sim 0.3$, which is not far from that between Source SW and the nominal center of Kes 17.

It is interesting to compare the detected fluxes between these two SNRs. The observed energy flux at GeV of W28 is $\sim 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ and that of Kes 17 is $\sim 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. The square of the distance ratio between these two SNRs is $(9.7/1.9)^2 \sim 26$, which makes the intrinsic GeV luminosities of these two SNRs within a factor of two. W28 has also been detected in TeV (Aharonian et al. 2008) and its spectrum from GeV to TeV can be roughly connected by a single spectral index $\sim 2.3$. If the radiation processes of Kes 17 and W28 are indeed similar, we can extrapolate the detected GeV flux of Kes 17 to predict the TeV flux. Using the best-fit spectral parameters, the extrapolated energy flux at TeV is $\sim 6 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, which is roughly 1% of the Crab flux and is detectable at the 3$\sigma$ level in 20 hr of H.E.S.S. observations (Aharonian et al. 2006). As Kes 17 is located within the field of view of H.E.S.S. when observing PSR B1259-63 for $\sim 100$ hr (cf. Aharonian et al. 2005b, 2009), the extrapolated energy flux at TeV of Kes 17 should have been reported. Based on the non-detection of Kes 17 by H.E.S.S., we estimate the limiting integrated photon flux above 1 TeV of Kes 17 to be $\sim 2 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ at a confidence level of $99\%$. If this is indeed the case, this may suggest that either the cutoff energy is $<\text{TeV}$ or the GeV and TeV energy ranges cannot be described by a single PL. On the other hand, we note that the errors of spectral parameters inferred in this analysis are rather large. Such uncertainties are magnified in extrapolating to the TeV regime. Within 1$\sigma$ errors, the extrapolated flux at TeV can go down to $\sim 6 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, which is below the detection threshold of H.E.S.S.

In a competitive scenario, the observed $\gamma$-rays can also have a leptonic origin. One typical example is RX J1713.7-3946 (Abdo et al. 2011). Its GeV–TeV spectral energy distribution is fully consistent with that predicted by the leptonic models (Abdo et al. 2011). On the other hand, the hadronic models show bumps in the range between a few hundred MeV and a few GeV (see Figure 3 in Abdo et al. 2011). For a leptonic scenario, the main channel is through the inverse Compton scattering of the surrounding soft photon fields by the relativistic electrons. These relativistic electrons are also expected to emit synchrotron X-rays. This provides a natural explanation for the similar emission morphology of RX J1713.7-3946 in the X-ray and $\gamma$-ray regimes (Abdo et al. 2011 and references therein).

While the X-ray emission of RX J1713.7-3946 is non-thermal dominant (Koyama et al. 1997; Slane et al. 1999; Tanaka et al. 2008), the X-rays from Kes 17 are essentially thermal with weak ($\sim 8\%$) non-thermal contributions (Combi et al. 2010), which makes the leptonic scenario questionable. Nevertheless, we have to point out that soft X-ray emission ($\sim 0.1–10$ keV) is typically dominated by shock-heated plasma, which makes the search for the non-thermal contribution difficult and uncertain. The upcoming X-ray observatories with hard X-ray imaging capabilities, such as NuSTAR (Harrison et al. 2010), can provide a clean channel for tightly constraining the X-ray synchrotron component in Kes 17.

Finally, we briefly discuss the nature of the $\gamma$-ray sources detected around Kes 17. The spectrum of Source E appears to be flatter than Kes 17. Also, it appears to be spatially disconnected from Kes 17 in Figure 3. Based on these properties, we suggest that Source E is a newly uncovered distinct object. For the other three sources, despite the fact that their spectral properties are similar to Kes 17, their connection with the SNR cannot be firmly established solely based on the $\gamma$-ray observation. Observations in other frequencies, particularly radio and X-ray band, are needed for identifying their nature.

Among the three of them, Source SW is the most interesting one as several objects have been found in its neighborhood. We examined whether it can be connected to HESS J1303-631 by comparing their spectral properties. The photon index of HESS J1303-631 ($\Gamma \sim 2.44$ Aharonian et al. 2005a) is similar to that of Source SW inferred in the GeV regime. But the extrapolated flux of Source SW in the 0.3–10 TeV band with its best-fit parameters is $\sim 4.5 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, which is $\sim 50$ times smaller than the observed flux of HESS J1303-631 in the same band ($\sim 2.1 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$; Aharonian et al. 2005a). Such discrepancy cannot be reconciled within the 1$\sigma$ errors of the spectral parameters. Therefore, the association of Source SW and HESS J1303-631 is unlikely. On the other hand, IRAS 13010-6254 apparently coincides with the peak of Source SW with an offset $\sim 0.075$ (see Figures 1 and 3). This infrared source is identified as a star formation region (Avedisova 2002). This makes Source SW resemble Source S near W28 to a further extent as this source is also found to spatially coincide with the compact H II region W28A2 (Abdo et al. 2010c). A multiwavelength campaign in the future is required to probe the nature of these sources as well as their possible connection with the SNR.

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