Discovery of gamma-ray emission from the supernova remnant Kes 17 with *Fermi* Large Area Telescope

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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 well described by a simple power-law with a photon index of $\Gamma \sim 2.4$. Together with the multi-wavelength 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.

Subject headings: acceleration of particles — cosmic rays — Gamma-rays: ISM — ISM: Individual objects (Kes 17, G304.6+0.1) — ISM: supernova remnants

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 the 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

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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 its spectrum (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 is 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 milli-gauss 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 Fig. 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 π^0 produced in the collision of the accelerated hadrons. Therefore, increasing supports for SNRs as the acceleration site have been found by $\gamma-$ray observations in the recent years.

Thanks to the ground-based observatories, such as H.E.S.S., 17 SNRs have so far been detected in 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 (π^0-decay, bremsstrahlung and/or inverse Compton due to electrons) in TeV band, the debate on whether the origin of this high energy emission is hadronic or leptonic remains.

The spectrum between ~ 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) onboard 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. Tab. 1 in Caprioli 2011 and reference therein). A number of investigations do favor the scenario of π^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 the detectability, we particularly focus on those SNRs have interaction 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 remnant.

Kes 17 (G304.6+0.1) was firstly detected in 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 a irregular shell morphology which was suggested as a results of the collision of the SNR shock front and its dense environment (Milne et al. 1985; White & Green 1996). This scenario was supported by the detection of 1720 MHz OH maser in its direction (Frail et al. 1996). In an infrared survey of SNRs in the inner region of Milky Way, Kes 17 was detected with the images obtained by *Spitzer* Space Telescope (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 of $(2.8 - 6.4) \times 10^4$ yrs old. On the other hand, no TeV emission have so far 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 & RESULTS

In this analysis, we used the LAT data between 2008 August 4 and 2011 January 31. To reduce and analysis 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. The instrumental response functions (IRFs) "P6_V3_DIFFUSE" were adopted throughout this study.

Events were selected within a circular region-of-interest (ROI) centered at the nominal position of Kes 17 (i.e. RA=$13^h05^m59.0^s$ Dec=$-62^\circ42^{'}18.0^{''}$). Owing to its proximity to the Galactic plane and the crowded environment, the size of ROI with a diameter of 10° was adopted throughout the analysis in order to reduce systematic uncertainties due to inaccurate background subtraction in this complex region. A binned photon count map in $0.1 - 100$ GeV was firstly produced with task *gtbin* for a preliminary visual inspection (Figure 1). A $\gamma-$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, $\gamma-$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 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 can 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 an infrared source IRAS 13010-6254 close to the peak of the southwestern excess.

Before we proceeded to analyse the emission nature of Kes 17, we firstly 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 locate within the ROI were set to be free, we kept the parameters for those lie 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 $\sim 15\sigma$ in the ~ 30 months data. We then proceeded to reexamine the emission properties of these sources, we performed a detailed spectral analysis with Kes 17 included in the model.

In order to minimize the contamination due to PSF wings of surrounding sources, we restricted all the subsequent analysis in $1 - 20$ GeV for obtaining robust results. We firstly 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 $\Gamma = 2.42 \pm 0.16$, a prefactor of $(1.80 \pm 1.05) \times 10^{-9}$ 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 $(4.7 \pm 0.7) \times 10^{-9}$ cm^{-2} s^{-1} The corresponding integrated energy flux is $f_\gamma = 1.9^{+3.4}_{-1.5} \times 10^{-11}$ erg cm^{-2} s^{-1} [5]. With the full energy range of $1-20$ GeV divided into 5 logarithmically equally-spaced energy bins, the binned spectrum is constructed from the indpendent fits of each bin which is displayed in Figure 2. Besides a simple PL model, we have also examined if 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 value of 146 and 145 respectively. Based on the likelihood ratio test, the additional spectral parameters in EPL/BKPL are not statistically required for describing the observed γ-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 index (photon flux) of 1FGL J1309.9-6229c and 1FGL J1301.4-6245c are $\Gamma = 2.32 \pm 0.18$ ($(3.6 \pm 0.6) \times 10^{-9}$ cm^{-2} s^{-1}) and $\Gamma = 2.63 \pm 0.18$ ($(3.7 \pm 0.6) \times 10^{-9}$ cm^{-2} s^{-1}) respectively. Their significances are lowered to $\sim 9\sigma$ and $\sim 8\sigma$ respectively.

We have computed the 2°× 2° TS map in 1-20 GeV centered at the nominal position of Kes 17 by using *gttsmap*. This is shown in Figure 3. With the aid of *gtfindsrc*, We determined the best-fit position in $1-20$ GeV to be RA=$13^h05^m55.01^s$ Dec=-62°39$^{'}$49.7$^{''}$ (J2000) with 1σ error radius (statistical) of 0.042°which is illustrated with 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 as Source SW hereafter). And the other feature which located on the eastern side appears to be a distinct source (referred as Source E hearafter). The emission of sources SW and E is peaked at RA=$13^h04^m11.0^s$ Dec=-63°14$^{'}$52.9$^{''}$ (J2000) and RA=$13^h10^m39.0^s$ Dec=-62°47$^{'}$08.7$^{''}$ (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 significances 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-done the unbinned likelihood analysis. We summarize the properties of Kes 17 as well as the nearby source in Table 1.

[5]The quoted errors of the energy flux have taken the statistical uncertainties of both photon index and prefactor into account.

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 power-law with a photon index of $\Gamma \sim 2.4$.

We have also found various γ-ray sources in the vicinity of Kes 17 (cf. Table 1 and Fig. 3). It is quite difficult to confirm if they have actual physical connections because Kes 17 is one of most poorly studied SNR. However we can compare Kes 17 and W28, which share the following similarities. Both of them are middle-age SNR which have an age of $\sim 10^4$ years. In the case of W28, besides the GeV emission from the nominal position of the SNR (i.e. Source N in Abdo et al. 2010c), another GeV source have been detected outside the southern boundary of W28 (i.e. Source S in Abdo et al. 2010c). Source S and Source N are apparently spatially connected. In this aspect, the Source SW close to Kes 17 resembles the Source S in the case of W28 (cf. Abdo et al. 2010c; Giuliani et al. 2010). For the Source S of W28, one possible scenario of the γ-ray emission is suggested by the runaway CR model (Ohira et al 2011; Abdo et al. 2010c). In this scenario, the MCs are illuminated by the CRs that escaped from the SNR in earlier epochs. If this is indeed the case, systems like Kes 17 and W28 can enable us to study how the CRs are released in SNRs as well as their propagation in the ISM.

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 $D_{\rm ISM} \simeq 10^{28}\left(\frac{pc}{10\ {\rm GeV}}\right)^{0.5}$ cm^2 s^{-1}, where p is the CR momentum (cf. Ohira et al. 2011; Berezinskii et al. 1990). Adopting the remnant age of $t_{\rm SNR} \sim 5\times10^4$ yrs (Combi et al. 2010), the diffusion scale is estimated as $l_{\rm CR} \sim \sqrt{D_{\rm ISM} t_{\rm SNR}} \sim 40$ pc for the CRs with energies of ~ 10 GeV. At the distance of 9.7 kpc, this translates into an angular separation of $\sim 0.3^\circ$ which is not far from that between Source SW and nominal center of Kes 17.

Table 1. $\gamma-$ray properties of Kes 17 and the nearby sources in $1-20$ GeV.

Source	Γ	f_γ $(1-20$ GeV$)$ 10^{-9} ph cm^{-2} s^{-1}	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

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 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 2. 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 ~ 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 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 5σ level in 20 hours of H.E.S.S. observations (Aharonian et al. 2006). As Kes 17 is located within the FoV of H.E.S.S. when observing PSR B1259-63 for ~ 100 hrs (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 $\sim 2 \times 10^{-13}$ cm^{-2} s^{-1} at a confidence level of 99%. If this is indeed the case, this may suggest that either the cut-off energy is $<$TeV or the GeV and TeV energy ranges cannot be described by a single power law. On the other hand, we notice that the errors of spectral parameters inferred in this analysis is rather large. Such uncertainties is magnified in extrapolating to the TeV regime. Within 1σ 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 hundreds MeV and a few GeV (see Fig. 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 the natural explanation for the similar emission morphology of RX J1713.7-3946 in 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 a 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 the shock-heated plasma which makes the search for the non-thermal contribution difficult and uncertain. The upcoming X-ray observatores 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 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 GeV regime. But the extrapolated flux of Source SW in $0.3 - 10$ 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 1σ 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 $\sim 0.075^{\circ}$(see Fig 1 & 3). This infrared source is identified as a star formation region (Avedisova 2002). This makes Source SW resembles the 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). Multiwavelength campaign in the future is required to probe the nature of these sources as well as to their possible connection with the SNR.

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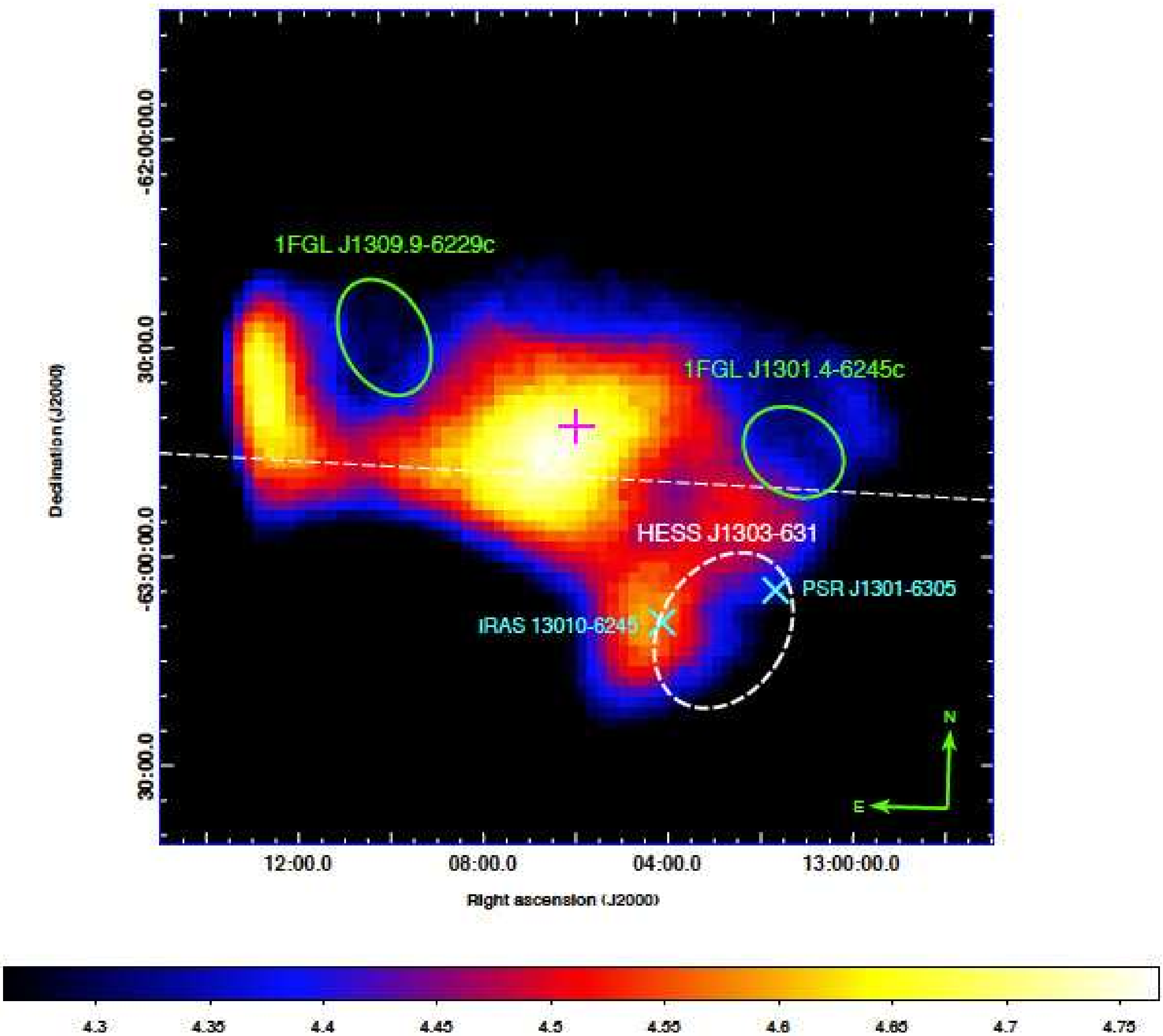

Fig. 1.— 2°×2° LAT count map in 0.1-100 GeV centered at Kes 17 with a pixel size of 0.025°, smoothed by a Gaussian kernel of 0.17°. The cross at the center represents the nominal position of Kes 17. The diameter of Kes 17 is $\sim 8'$ which corresponds to ~ 5 pixels in this map (Green 2009). The orientation of the Galactic plane is illustrated by the white dashed line. Positions of various sources are illustrated. The scale bar indicates the value of counts/pixel. No background subtraction has been applied.

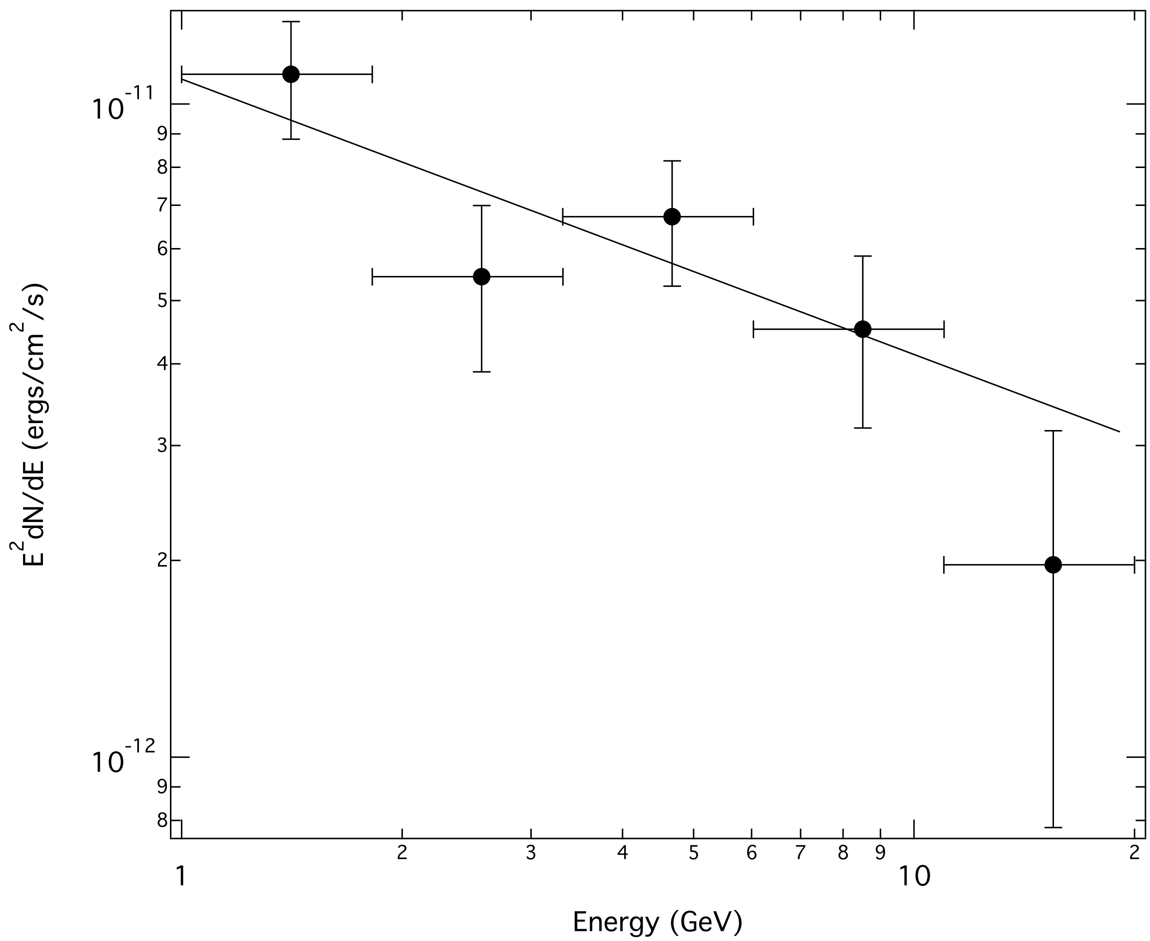

Fig. 2.— *Fermi* LAT spectrum of Kes 17. The full energy range $1 - 20$ GeV is divided into 5 energy bins. The data points and the vertical error bars correspond to independent fits in the respective bins. The solid line represents the best-fit power-law model inferred in the full energy band (i.e. $\Gamma = 2.42$).

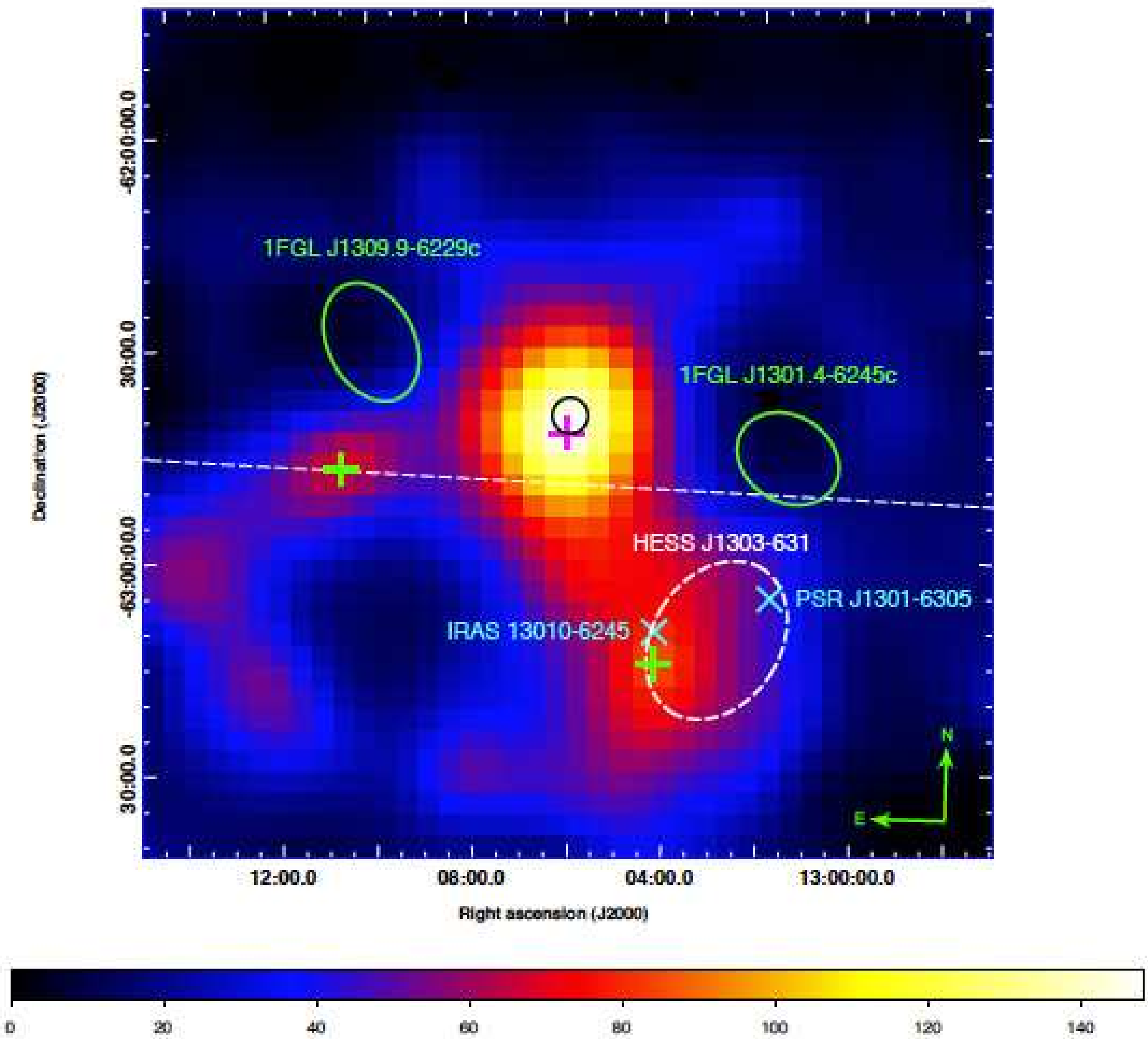

Fig. 3.— Test-statistic (TS) map in 1-20 GeV of a region of $2^\circ \times 2^\circ$ centered at the nominal position of Kes 17 (magenta cross). The peak emission of the southwestern and the eastern features are marked with green cross. Positions of various sources are also illustrated. The color scale bar is used to indicated the TS values. The circle in black represents the 1σ positional error circle determined by *gtfindsrc*.