EXPLORING THE DARK ACCELERATOR HESS J1745-303 WITH THE FERMI LARGE AREA TELESCOPE

C. Y. Hui\textsuperscript{1}, E. M. H. Wu\textsuperscript{2}, J. H. K. Wu\textsuperscript{2}, R. H. H. Huang\textsuperscript{1}, K. S. Cheng\textsuperscript{2}, P. H. T. Tam\textsuperscript{1}, and A. K. H. Kong\textsuperscript{3,4}

\textsuperscript{1} Department of Astronomy and Space Science, Chungnam National University, Daejeon 305-764, Republic of Korea
\textsuperscript{2} Department of Physics, University of Hong Kong, Pokfulam Road, Hong Kong, China
\textsuperscript{3} Institute of Astronomy and Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
\textsuperscript{4} Golden Jade Fellow of Kenda Foundation, Taiwan

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ABSTRACT

We present a detailed analysis of the $\gamma$-ray emission from HESS J1745-303 with the Fermi Gamma-ray Space Telescope in its first $\sim$29 month observation. The source can clearly be detected at the levels of $\sim 18\sigma$ and $\sim 6\sigma$ in 1–20 GeV and 10–20 GeV, respectively. We do not find any evidence of the variability seen in the results obtained by the Compton Gamma-ray Observatory. Most of the emission in 10–20 GeV is found to coincide with region C of HESS J1745-303. A simple power law is sufficient to describe the GeV spectrum with a photon index of $\Gamma \sim 2.6$. The power-law spectrum inferred in the GeV regime can be connected to that of a particular spatial component of HESS J1745-303 in 1–10 TeV without any spectral break. These properties impose independent constraints for understanding the nature of this “dark particle accelerator.”

Key words: gamma rays: ISM – ISM: individual objects (HESS J1745-303, G359.1-0.5, 3EG J1744-3011)

Online-only material: color figure

1. INTRODUCTION

Recent surveys of the central region of our Galaxy with the High Energy Stereoscopic System (H.E.S.S.) have uncovered a number of $\gamma$-ray sources in the TeV regime (Aharonian et al. 2002, 2005a, 2005b, 2006a). Unlike pulsar wind nebulae (PWNe) and young supernova remnants (SNRs), non-thermal X-ray counterparts have not yet been identified for some of these sources. HESS J1745-303 is one of the most enigmatic objects among them.

HESS J1745-303 was first discovered by the H.E.S.S. Galactic Plane Survey (Aharonian et al. 2006a) and was subsequently investigated in detail with dedicated follow-up observations (Aharonian et al. 2008). The TeV $\gamma$-ray image shows that it consists of three spatial components (regions A, B, and C in Figure 1 of Aharonian et al. 2008). Owing to the lack of spectral variability and the insignificant dip among these regions in the existing data, it has been argued that they originated from a single object (Aharonian et al. 2008). This inference suggests that HESS J1745-303 is one of the largest unidentified TeV sources, with an angular size of $\sim 0.3 \times 0.5$.

Searches for the possible non-thermal diffuse X-ray component in region A of HESS J1745-303 have been conveyed with XMM-Newton and Suzaku (Aharonian et al. 2008; Bamba et al. 2009). None of these observations have resulted in any evidence for the diffuse X-ray emission. This imposes a TeV-to-X-ray flux ratio larger than $\sim 4$ (Bamba et al. 2009), which is larger than the typical value of PWNe and SNRs (i.e., less than 2; cf. Matsumoto et al. 2007; Bamba et al. 2007, 2009). Because of the non-detection of counterparts in X-ray/radio, HESS J1745-303 was dubbed a “dark accelerator” (Bamba et al. 2009).

While a non-thermal diffuse X-ray emission has not yet been found, a possible excess of neutral iron line emission was discovered in the direction toward region A of HESS J1745-303 (Bamba et al. 2009). Due to its proximity to the Galactic center and the positional coincidence of a molecular cloud (Aharonian et al. 2008), the line emission is suggested to be reflected X-rays originating from previous activity in the Galactic center (Bamba et al. 2009). The molecular cloud can interact with the shock from a nearby SNR G359.1-0.5 (Bamba et al. 2000, 2009; Lazendic et al. 2002; Ohnishi et al. 2011) and produce the observed $\gamma$-rays through the acceleration of protons and/or leptons (see Bamba et al. 2009). However, this proposed scenario cannot be confirmed unambiguously. In view of the presence of many surrounding objects (see Figure 1 in Aharonian et al. 2008), including the “mouse” pulsar (i.e., PSR J1747-2958), one cannot rule out these objects as the source of energetic particles based solely on the TeV results (Aharonian et al. 2008). Furthermore, with the current information, it is not possible to discriminate between a hadronic model and a leptonic model (see Figures 5 and 6 in Bamba et al. 2009). In order to do so, investigations in the lower energy regime are required.

It is interesting to note that HESS J1745-303 is positionally coincident with an unidentified EGRET source 3EG J1744-3011 (Hartman et al. 1999). Unlike HESS J1745-303, 3EG J1744-3011 was suggested to demonstrate long-term variability (Torres et al. 2001). Also, based on the MeV–GeV spectrum observed by EGRET, the extrapolated flux in the TeV regime overshoots that observed by H.E.S.S. Therefore, Aharonian et al. (2008) concluded that 3EG J1744-3011 is unrelated to HESS J1745-303.

After the commencement of the Large Area Telescope (LAT) onboard Fermi Gamma-ray Space Telescope, which has much improved spatial resolution and sensitivity, a detailed investigation of this dark accelerator in the MeV–GeV regime is now feasible. However, among 1451 objects detected by LAT during the first 11 months, we did not identify any source corresponding to HESS J1745-303/3EG J1744-3011 (Abdo et al. 2010a). Very recently, in an analysis of the $\gamma$-rays from the Galactic center using data from the first 25 months of LAT observations, a new source was found to coincide spatially with HESS J1745-303/3EG J1744-3011 (Chernyakova et al. 2011). In this paper, we report a detailed analysis of this source using data from the first $\sim$29 months of LAT observations.
2. DATA ANALYSIS AND RESULTS

In this analysis, we used the data obtained by LAT between 2008 August 4 and 2010 December 23. The Fermi Science Tools v9r18p6 package was used to reduce and analyze the data in the vicinity of HESS J1745-303. Only the events that are classified as class 3 or class 4 were adopted. The post-launch instrument response functions “P6_V3_DIFFUSE” were used throughout this investigation.

With the aid of the task gtlke, we performed unbinned maximum-likelihood analysis for a circular region-of-interest (ROI) with a 10° diameter centered on the nominal position of HESS J1745-303 (i.e., RA = 17°45′19.999, decl. = −30°22′12.0′′ (J2000)). The size of the ROI was chosen to avoid the surrounding bright sources, thereby reducing systematic uncertainties due to inaccurate background subtraction in this complex region. To subtract the background contribution, we included the Galactic diffuse model (gll_iem_v02.fit) and the isotropic background (isotropic_iem_v02.txt), as well as 41 sources in the first Fermi/LAT catalog (1FGL; Abdo et al. 2010a) within 10° from the aforementioned center.

To begin, we compared the spectral properties inferred by LAT and EGRET. For a consistent comparison with Hartman et al. (1999), we used events with energies >100 MeV for our initial analysis. We assumed a power law (PL) spectrum for HESS J1745-303 as well as for all 1FGL sources in our consideration. All the sources were assumed to be point sources throughout this investigation. The best-fit model yielded a photon index of $\Gamma = 2.16 \pm 0.03$ and a test-statistic (TS) value of 499, which corresponds to a significance of 22σ. This is consistent with the significance reported in the preliminary analysis by Chernyakova et al. (2011). The photon index was found to be consistent with 3EG J1744-3011 (i.e., $\Gamma = 2.17 \pm 0.08$). To further compare with the EGRET results, we computed the integrated photon flux in 0.1–10 GeV, which was found to be $2.06^{+0.24}_{-0.23} \times 10^{-7}$ cm$^{-2}$ s$^{-1}$. This is ~3 times smaller than that of 3EG J1744-3011 (i.e., $6.39 \pm 0.71 \times 10^{-7}$ cm$^{-2}$ s$^{-1}$). The discrepancy may be due to the improved spatial resolution of LAT: hence, the estimation of background contribution from the nearby sources is more accurate than EGRET.

Considering the background, as HESS J1745-303 is located close to the Galactic center, where diffuse γ-ray emission is very intense, the contamination can possibly be large at lower energies. Also, the point-spread function (PSF) of LAT is narrower at higher energies. While the 68% containment radius at 100 MeV is ∼4:5, it is only ∼0:8 at 1 GeV. Therefore, the contamination due to the PSF wings of the nearby sources can be minimized by limiting the analysis to higher energies. In order to minimize the systematic uncertainty in the background modeling and obtain robust results, we restricted the subsequent analysis to 1–20 GeV. In this adopted band, the best-fit PL model resulted in a TS value of 332, which corresponds to a detection significance of ~18σ. To examine the robustness of the detection, we considered the systematic uncertainty of the Galactic diffuse emission background. Following Abdo et al. (2010a), we repeated the analysis by varying the slope and the normalization of the Galactic diffuse model in 0.07 and ±10%, respectively. Within the uncertainty of the background model, the detection significance remained over 10σ.

5 All errors quoted in this paper are statistical only and are computed for a confidence interval of 1σ.

6 For updated status, please refer to http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure1}
\caption{Fermi LAT spectrum of HESS J1745-303. The solid line represents the best-fit power-law model.}
\end{figure}

fit PL model yielded a photon index of $\Gamma = 2.60 \pm 0.05$ and an energy flux of $5.25^{+1.87}_{-1.47} \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in 1–20 GeV. The best-fit PL model and the γ-ray spectrum as seen by Fermi LAT are shown in Figure 1.

In addition to considering the simple PL model, we also examined whether a broken power law (BKPL) or an exponential cutoff power law (PLE) can better describe the spectrum. The fittings with BKPL and PLE resulted in the TS values of 335 and 333, respectively. Based on the likelihood ratio test, the additional spectral parameters in BKPL/PLE are not strongly required, which suggests that a single PL is statistically sufficient to describe the data. For the PLE model, the best-fit photon index and cutoff energy are $\Gamma = 2.31 \pm 0.07$ and $E_{\text{cutoff}} = 12.63 \pm 4.69$ GeV, respectively. On the other hand, for the BKPL model, the initial fitting resulted in a break energy and photon indices of $E_{\text{break}} = 3.68 \pm 0.22$ GeV, $\Gamma_1 = 2.32 \pm 0.15$, and $\Gamma_2 = 3.09 \pm 0.26$, respectively. However, unlike the best-fit solutions inferred from PL and PLE models, the solution inferred from the BKPL fit is unstable, subject to perturbations in the parameter space. In view of this problem of convergence, we will not further consider the BKPL model in subsequent analyses.

Although the extra parameter, $E_{\text{cutoff}}$, in the PLE model is not statistically required, one is not able to completely rule it out in view of its capability in depicting the observed data. As a PLE model typically describes the γ-ray spectrum of a pulsar (Abdo et al. 2010b, 2011), we speculate that there may be a hidden pulsar in HESS J1745-303. To test this hypothesis, we performed a blind search for coherent pulsation. The arrival times of each photon were barycentrically corrected, with the nominal position of HESS J1745-303 adopted. To minimize the impact due to ignorance of the spin-down rate, we divided the full time span of the adopted data into five segments and ran the Fourier analysis in each segment independently with the aid of the tool gtpec. From each computed power spectrum, we picked up 10 peaks and investigated whether there is any correlation among different segments. We did not identify any promising periodicity candidate in these data. Hence, we conclude that there is no evidence for a hidden pulsar in HESS J1745-303.

As 3EG J1744-3011 was reported to be a variable (Torres et al. 2001), we also examined the variability with LAT data.
First, we extracted the light curve obtained from the data within 1° of the nominal position of HESS J1745-303 with a binning factor of 10 days in the energy range of 1–20 GeV. By fitting a horizontal line to the light curve, we obtained a reduced $\chi^2$ of 1.5 for 87 degrees of freedom. Hence, there is no strong evidence for any variability or flaring.

For a further investigation of the possible spectral and flux variability, we divided the whole data set into five segments of equal time spans and performed an unbinned likelihood analysis on each segment. The results are summarized in Table 1. A simple PL was adopted for all the fittings. Within the tolerance of the statistical uncertainties, we conclude that neither the spectral shape nor the flux varies among these segments.

We computed the $2^\circ \times 2^\circ$ TS map in 1–20 GeV centered at the nominal position of HESS J1745-303 by using the tool gttsmap. This is displayed in Figure 2(a). Utilizing gtfindsrc, we determined the best-fit position in 1–20 GeV to be R.A. = 17h43m44s1440 and decl. = −30°20′32″/28 (J2000) with a 1σ positional error radius of 0:05. The position is located between regions A and C of HESS J1745-303. Given that the PSF has a 68% containment radius of ∼0.8 at 1 GeV, the source extent inferred in this band is consistent with that of a point source. The relatively wide PSF does not allow us to determine whether GeV emission is associated with any particular TeV feature. To further examine the spatial nature, we also computed the TS map in 10–20 GeV, which is displayed in Figure 2(b). Since the 68% containment radius at 10 GeV is ∼4 times smaller than that at 1 GeV, the feature can be better resolved. We found that the peak TS value found in this band is 41, which corresponds to a significance of ∼6σ. Within the systematic uncertainty of the Galactic diffuse background, we found that the detection significance of the source remains over 4σ in this band. The best-fit position in 10–20 GeV was found to be R.A. = 17h43m44s160 and decl. = −30°26′24″/00 (J2000) with a 1σ error radius of 0:05. This differs from that inferred in 1–20 GeV by 0:2. We note that the GeV feature found in this hard band apparently peaks at region C and possibly extends to region B. Although it appears to be extended in the hard band, the relatively low detection significance in this energy range does not allow a firm conclusion.

### Table 1

| Time Segment | $f^a_\gamma$ (1–20 GeV) | $10^{-11}$ erg cm$^{-2}$ s$^{-1}$ |
|--------------|-------------------------|-------------------------------|
| 239557417–254601478.2 | 2.67 ± 0.23 | 4.45$^{+12.93}_{-3.96}$ |
| 254601478.2–269645539.4 | 2.45 ± 0.18 | 6.65$^{+14.28}_{-5.16}$ |
| 269645539.4–284689600.6 | 2.57 ± 0.05 | 5.73$^{+2.2}_{-1.7}$ |
| 284689600.6–299733661.8 | 2.70 ± 0.25 | 5.02$^{+16.15}_{-4.0}$ |
| 299733661.8–314777723 | 2.80 ± 0.30 | 4.35$^{+19.16}_{-4.28}$ |

Note. * The quoted errors of energy have taken the statistical uncertainties of both photon index and pre-factor into account.

### Figure 2

(a) Test-statistic (TS) map in 1–20 GeV of a region of $2^\circ \times 2^\circ$ centered at the nominal position of HESS J1745-303. The color scale used to indicate the TS value is shown by the scale bar below the images. The blue circle represents the 1σ positional error circle determined by gtfindsrc. Various TeV emission components of HESS J1745-303 (regions A, B, and C in Figure 1 of Aharonian et al. 2008) are illustrated by the black dashed circles. (b) Same as Figure 2(a) but in the energy range of 10–20 GeV.

(A color version of this figure is available in the online journal.)

3. DISCUSSION

In this paper, we have reported a detailed study of HESS J1745-303 with *Fermi* LAT data, which provides a missing piece in understanding the nature of this dark accelerator. In view of the putative variability of 3EG J1744–3011, Aharonian et al. (2008) argued that the GeV counterpart is unlikely to be associated with HESS J1745-303. However, we do not find any evidence for spectral/flux variability from the LAT data. The discrepancy between the LAT result and that inferred from EGRET is most likely due to the differences in their...
J1747.2-2958, the photon index inferred from the LAT data (i.e., in the GeV regime with those obtained by H.E.S.S. First, et al. 2010a), the source confusion in the EGRET data may ∼ sources within the proximity of HESS J1745-303 are now detected. As several and sensitivity of LAT, many previously unknown sources in instrumental performance. With the improved angular resolution data sets.

Figure 3. Spectral energy distribution of HESS J1745-303 as observed by Fermi LAT and H.E.S.S. The H.E.S.S. spectrum is for region A. The solid line represents the best-fit power-law model inferred in the joint analysis of both data sets.

It is interesting to compare the spectral properties inferred in the GeV regime with those obtained by H.E.S.S.. First, the photon index inferred from the LAT data (i.e., Γ = 2.60 ± 0.05) is similar to that inferred in TeV (cf. Table 2 of Aharonian et al. 2008). Furthermore, the extrapolated photon flux in 1–10 TeV with the best-fit PL model is found to be (2.21^{+1.84}_{-0.91}) × 10^{-13} cm^{-2} s^{-1}, which is consistent with any individual spatial component observed by H.E.S.S. within 1σ uncertainties (cf. Table 2 of Aharonian et al. 2008).

Since the TeV spectral data of region A are available (cf. Figure 2 of Aharonian et al. 2008), we further compare this particular region with the GeV spectrum by constructing a spectral energy distribution, which is displayed in Figure 3. Both data sets can be fitted simultaneously with a single PL of Γ = 2.63 ± 0.03. This clearly demonstrates that the TeV spectrum of this spatial component can be smoothly connected to the GeV spectrum.

For regions B and C, despite the fact that no TeV spectral data are currently available, we note that their spectral shapes, reported by Aharonian et al. (2008), are similar to those of region A. Within the statistical uncertainties of the spectral properties inferred in both the GeV and TeV regimes, the TeV spectra of these regions can also possibly be connected to those of GeV. Further investigation by H.E.S.S. is strongly encouraged, particularly for region C, as most of the γ-ray emission in 10–20 GeV apparently coincides with this spatial component.

As both PL and PLE models can describe the GeV spectrum equally well, we cannot discriminate between these competing models based on the current data. In view of the exponential cutoff, the spectral connection between the GeV and TeV regimes cannot be established with the PLE model. However, we would like to point out that the best-fit cutoff energy, $E_{\text{cutoff}} = 12.63 \pm 4.69$ GeV, falls in the highest energy bin of the LAT spectrum (cf. Figure 1 and Figure 3). Owing to the small photon statistics in the hard band, the statistical uncertainty of the highest energy bin is rather large. In view of this, it remains unclear whether the inferred cutoff is genuine, as this particular data point is sensitive to the systematic uncertainty of the background. Analysis of the LAT data in higher energies (e.g., >10 GeV) with sufficient photon statistic in the future can help to discriminate between these two models.

The detection of γ-rays provides strong evidence for particle acceleration. It should be noted that around HESS J1745-303 there are two SNRs and two pulsars that can be the potential high energy particle injector (cf. Figure 1 of Aharonian et al. 2008). Based on the small distances of G359.0-0.9 and PSR B1742-30, Bamba et al. (2009) argued that these sources are foreground objects that are unrelated to HESS J1745-303. With the GeV counterpart revealed by LAT, we can now safely rule out the possibility that PSR B1742-30 is the major contributor. Its spin-down flux, $E/4\pi d^2 \sim 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, is lower than the energy flux observed in the GeV regime (cf. Manchester et al. 2005). On the other hand, for PSR J1747-2958, the sum of the γ-ray flux of 1FGL J1747.2-2958 and HESS J1745-303 observed by LAT only consumes ∼5% of its spin-down flux (∼3 × 10^{-14} erg cm$^{-2}$ s$^{-1}$). Therefore, it is energetically possible that it is the source for the high energy particles. Nevertheless, with its eastward proper motion (Hales et al. 2009), its backward extrapolated position is found by its spin-down age to have an offset of ∼0.6 and ∼0.8 from the best-fit positions inferred in 1–20 GeV and 10–20 GeV, respectively. If the feature found by H.E.S.S. and LAT is indeed a PWN, then it is one of the more peculiar systems because of its large positional offset with respect to the pulsar position.

While the contribution of PSR J1747-2958 is uncertain, the interaction between the shock from G359.1-0.5 and a molecular cloud in its neighborhood is considered to be a more viable means to produce the observed γ-rays. For both hadronic and leptonically accelerated scenarios, Bamba et al. (2009) modeled the broadband spectrum of region A of HESS J1745-303. Comparing Figure 1 in this paper and Figures 5 and 6 in Bamba et al. (2009), the GeV flux predicted in all the scenarios considered in their work is at least an order of magnitude lower than that observed by LAT. A revised theoretical investigation with constraints provided by LAT is therefore required. Moreover, while the remnant shells of other known systems of SNRs interacting with molecular clouds have been found in other wavelengths coinciding with the γ-ray emission (e.g., Castro & Slane 2010; Abdo et al. 2010c), there is no such evidence for HESS J1745-303. We should point out that all the previous multiwavelength campaigns were targeted only at the bright component of HESS J1745-303, namely, region A. Since the LAT observation suggests that the GeV emission possibly originates from regions C/B, observational investigations of these regions are encouraged for better understanding of this mysterious object.

Based on the above discussion, we must admit that the energy injection source of HESS J1745-303 remains unclear. It is instructive to compare it with other nearby high energy sources. Aharonian et al. (2006b) reported observations of an extended region of very high energy (>100 GeV) γ-ray emission correlated spatially with a complex of giant molecular clouds in the central 200 pc of the Milky Way. It appears that the TeV emissions from the molecular clouds in the vicinity of the Galactic Center are quite common phenomena. In addition, as in the case of HESS J1745-303, 6.4 keV lines from many
molecular clouds near the Galactic Center have been commonly detected, e.g., Sgr B2 (Koyama et al. 1996; Murakami et al. 2000), Sgr C (Murakami et al. 2001), and others (Bamba et al. 2002; Predehl et al. 2003; Nobukawa et al. 2008; Nakajima et al. 2009; Koyama et al. 2009). It has been speculated that these neutral iron lines arise from the reflection by the dense molecular clouds that are irradiated by nearby X-ray sources (e.g., Koyama et al. 2007; Inui et al. 2009). On the other hand, Dogiel et al. (2009) argued that these 6.4 keV lines from the molecular clouds are excited by a background intensity of subrelativistic protons coming from the escaped part of a star once captured by the Galactic supermassive black hole Sgr A*. The periodic stellar capture events may explain the recently observed Fermi bubble (Cheng et al. 2011). This subrelativistic proton wind can also form shock by hitting the clouds, producing relativistic protons. It is shown that the decay of neutral pions produced by hadronic collisions between the accelerated relativistic protons in the clouds can emit a power-law $\gamma$-ray spectrum from 30 MeV to 10 TeV without any spectral break (K. S. Cheng et al. 2011, in preparation). If this is true, then the high energy emissions from various molecular clouds in the vicinity of the Galactic center are correlated to the past activities of the Galactic center, and their intensity might be correlated with the propagation history of the injection of these subrelativistic protons escaped from the past capture events.

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