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Observation of multi-ten TeV to sub-PeV gamma rays from the HESS J1843-033 region with the Tibet air shower array

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The sky region around HESS J1843-033, a southern TeV gamma-ray source, is observed by the Tibet air shower array equipped with an underground muon detector array. The analysis makes use of the data taken from February 2014 to May 2017. A gamma-ray source TASG J1844-038 is detected above 25 TeV with a $6.2\,\sigma$ level, and its position is statistically consistent with that of nearby gamma-ray sources including HESS J1843-033. The energy spectrum is measured for the first time between 25 and 130 TeV and is described with $\mathrm{d}N/\mathrm{d}E = (9.70 \pm 1.89) \times 10^{-16} (E/40\,\mathrm{TeV})^{-3.26\pm0.30}\,\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The spectrum smoothly connects to that of HESS J1843-033 in the lower energy range and is consistent with the flux of LHAASO J1843-0338 at 100 TeV, and the fit to the combined spectra of the TASG, H.E.S.S., and LHAASO sources implies the cutoff at 49.5 ± 9.0 TeV in the gamma-ray spectrum. The association of TASG J1844-038 with a nearby supernova remnant G28.6-0.1 and a gamma-ray pulsar J1844-0346 is discussed.

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1. Introduction

Origin of cosmic rays in the knee region of the energy spectrum has been searched for through gamma-ray observation above 100 TeV (sub-PeV range). Since the detection of sub-PeV gamma rays from the Crab Nebula [1–3], more than a dozen of sub-PeV gamma-ray sources have been found in the northern sky [4–6]. In particular, the discovery of a prominent candidate for PeVatron supernova remnant (SNR) G106.3+2.7 [5, 7], the acceleration of ultra-high energy particles in the Cygnus region [8, 9], and the association of (UHE) gamma rays with energetic pulsars (PSR) [10] tell us that these source classes ubiquitous in our Galaxy indeed generate high energy particles. On the other hand, some of the sub-PeV gamma-ray sources discovered by LHAASO are unidentified [6, 11]; there is no likely counterpart for the sub-PeV sources. The Galactic Plane survey performed by H.E.S.S. also reveals that a large fraction of TeV gamma-ray sources are unidentified [12] and implies the existence of a particle acceleration mechanism that is not understood yet or an unknown class of sources. It should be noted that many of these unidentified sources are not sufficiently followed by observations and the interpretation of the mechanism of the gamma-ray emission is not discussed. In such a situation, more observational (multi-wavelength) studies can be fruitful to provide further information on the sources.

This study focuses on the gamma-ray observation of the sky region around HESS J1843-033, an unidentified gamma-ray source [12]. It has a complex morphology of gamma-ray emission and includes within its extension several SNR candidates discovered by the THOR survey [13] and PSR J1844-0346 [14]. eHWC J1842-035 and LHAASO J1843-0338 are detected near HESS J1843-033 above 56 TeV and at 100 TeV, respectively [4, 6], but their associations are not detailedly discussed. In particular, the energy spectrum of gamma rays from this sky region is not measured systematically above 30 TeV, which cannot be covered by H.E.S.S., and makes it difficult to interpret the relation between the above sources. The fraction of hadronic contribution to the gamma rays from this sky region is not well constrained with the neutrino observations [15]. This study investigates the gamma-ray emission from the aforementioned sky region utilizing the data taken by the Tibet air shower array equipped with an underground muon detector array and discusses its origin.

2. Experiment and Data Analysis

The Tibet air shower array has been working as a cosmic-ray observatory in the energy range above TeV since 1991 at Yangbajing (90.522° E, 30.102° N, 4,300 m a.s.l.), Tibet, China [16–18]. Its surface air shower array covering an area of 65,700 m^2 composes 597 plastic scintillation detectors with a 0.5 m^2 area, which detect particles in extensive air showers and allow us to determine the primaries' energies and incoming directions [19, 20]. The array is also equipped with an underground muon detector (MD) array with a total area of 3,400 m^2 [1]. The array contains a water layer with a 1.5 m depth and detects Cherenkov light emitted by shower muons passing through the water. The MD array serves to discriminate primary gamma rays and cosmic rays and realizes high sensitivity to gamma rays [21], which has been proved in previous studies [1, 5, 9, 22].

This study uses the data taken by the Tibet air shower array and the MD array from February 2014 to May 2017 which amounts to 719 live days. The data are selected with the criteria introduced by Amenomori et al. (2019) [1], except for the following conditions. First, the analyzed zenith-

Table 1: Information of TASG J1844-038 along with nearby gamma-ray sources previously detected

Source Name	Energy Range	α (°)	δ (°)	$R_{0.68}$ (°)[1]	Extension (°)	Angular Distance to TASG J1844-038 (°)	Reference
TASG J1844-038	> 25 TeV	291.09	-3.76	0.21	0.34 ± 0.12	-	-
HESS J1843-033	> 400 GeV	280.95	-3.55	0.12	0.24 ± 0.06	0.25 (1.0σ)	[12]
eHWC J1842-035	> 56 TeV	280.72	-3.51	0.30	0.39 ± 0.09	0.44 (1.2σ)	[4]
LHAASO J1843-0338	> 100 TeV	280.75	-3.65	0.15	-[2]	0.35 (1.4σ)	[6]

1 For the definition, see the text. For the pointing systematics of each experiment, [3, 28, 29] are referred
2 Extension is not published

angle range is extended up to 50° to increase statistics of gamma rays from the HESS J1843-033 region. This extension is found to be especially effective in the energy range above 25 TeV from our simulation study, and the threshold energy is thus accordingly fixed at 25 TeV. Finally, the selection using ΣN_μ, the total number of muons recorded with the MD array (MD cut), is optimized for this study; it requires events to satisfy $\Sigma N_\mu < 1.8 \times 10^{-3} (\Sigma\rho/\mathrm{m}^{-2})$ or $\Sigma N_\mu < 0.4$ where $\Sigma\rho$ is the sum of the particle number density recorded with the surface scintillation detectors. This cut is found to reduce the background cosmic rays to less than a 0.1% level.

In the Monte Carlo (MC) simulation, a total number of 1.1×10^8 gamma rays are generated following a power-law spectrum with an index of 2.0 using Corsika v7.4000 [23] and injected into the atmosphere from a hypothetical point source with a declination of 0° to simulate the development of air showers. The detector response for the showers is simulated with Geant4 v10.0 [24]. The energy loss of particles in the scintillators and the soil layer is calculated, and Cherenkov-radiation processes are simulated for the particles that reach MDs. From the MC data analysis, the energy and angular resolutions are estimated at ≃ 30% and 0.28° (50% containment), respectively. The optimum MD cut presented above keeps ≃ 80% of gamma rays in the 100 TeV range.

3. Results

The distribution of events in a 4° × 4° square region centered at $(\alpha, \delta) = (281.0°, -3.5°)$ (J2000) which includes HESS J1843-033 is modeled with a source component of an axisymmetric Gaussian plus the background component constructed from the data on the same declination band. Performing a two-dimensional unbinned maximum likelihood analysis, the center of a potential source is determined as $(\alpha, \delta) = (281.09° \pm 0.10°, -3.76° \pm 0.09°)$. A circular ON-source window with a radius of 0.7° are opened at the obtained center, and the excess of events in the window is counted against the average of 20 OFF regions opened with the equi-zenith-angle method [25]. The significance of excess in the ON-source window results in a 6.2 σ level [26], realizing a successful detection of a gamma-ray source. The source is named TASG J1844-038 and hereafter this name is used. Table 1 shows the information on TASG J1844-038 along with nearby gamma-ray sources. Source position uncertainty is evaluated in terms of error radius with the 68% confidence level calculated with the methodology presented by H.E.S.S. Collaboration (2018a) [27]. The result tells us that TASG J1844-038 is positionally consistent with HESS J1843-033, eHWC J1842-035, and LHAASO J1843-0338 and thus can be associated with these sources.

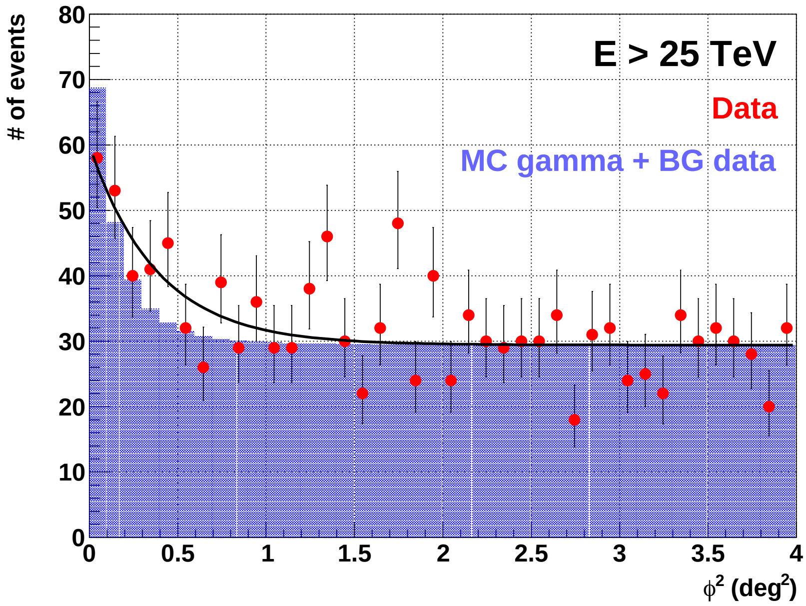

Figure 1: Radial distribution of events against the position of TASG J1844-038 compared with the blue histograms made of MC gamma-ray events from a point source plus background data. The black curve shows the Gaussian function fitted to the data. The figure is cited from Amenomori et al. (2022) [30].

The source extension is estimated from the one-dimensional radial profile of events against the source center as shown in Figure 1. The data points are fitted with a Gaussian shown with the black curve, which results in the source extension of $0.34^\circ \pm 0.12^\circ$ with $\chi^2/\mathrm{d.o.f.} = 39.5/38$. The result is consistent with the extensions of HESS J1843-033 and eHWC J1842-035 (see Table 1)

Figure 2 shows the energy spectrum of TASG J1844-038 measured between 25 and 130 TeV with the spectra of nearby gamma-ray sources. In each energy bin, the energy flux is calculated only if the significance of gamma-ray detection exceeds a $2\,\sigma$ level; otherwise, the 95% upper limit is calculated. Our result can be fitted with a simple power-law (PL) function, which gives $\mathrm{d}N/\mathrm{d}E = (9.70 \pm 1.89) \times 10^{-16} (E/40\,\mathrm{TeV})^{-3.26\pm0.30}\ \mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ with $\chi^2/\mathrm{d.o.f.} = 2.1/2$. The absolute energy scale uncertainty of 12% [18] and the statistical uncertainty in the source extension affect the flux normalization by 43% as a systematic error. It should be noted that the spectrum of the TASG source smoothly connects to that of HESS J1843-033 at 30 TeV and also gives the energy flux consistent with that of LHAASO J1843-0338 at 100 TeV. These facts imply the same origin for their gamma-ray emissions. Therefore, gamma rays from this sky region would be better characterized by performing a combined spectral fit between the spectra of the TASG, H.E.S.S., and LHAASO sources. The combined spectra disfavor the fit with a simple PL function at a $5\,\sigma$ level ($\chi^2/\mathrm{d.o.f.} = 47.3/9$), and is well described with the PL function with exponential cutoff;

$$\frac{\mathrm{d}N}{\mathrm{d}E} = N_0 \left(\frac{E}{\mathrm{TeV}}\right)^{-\Gamma} \exp\left(-\frac{E}{E_{\mathrm{cut}}}\right) \mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}. \quad (1)$$

The fit results in $N_0 = (3.57 \pm 0.26) \times 10^{-16}\,\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, $\Gamma = -2.02 \pm 0.06$, and $E_{\mathrm{cut}} =$

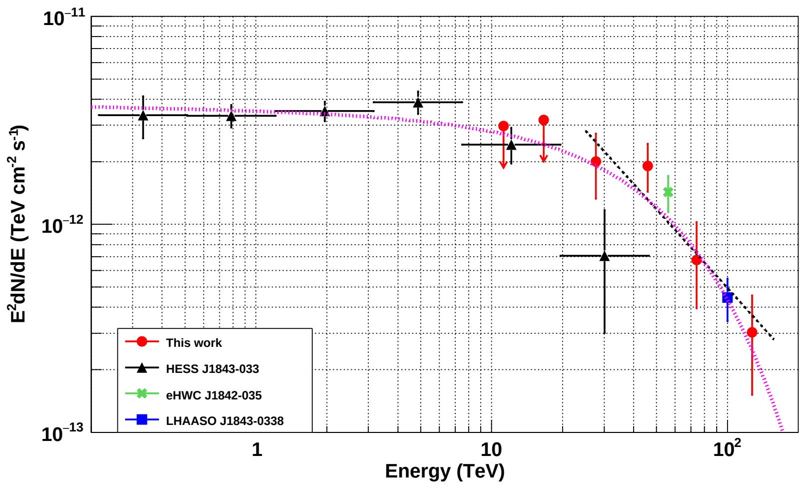

Figure 2: Energy spectra of TASG J1844-038 (red) and nearby gamma-ray sources [4, 6, 12]. The error bars are statistical and the downward arrows indicate the 95% upper limits. The black dotted line is the best-fit PL function to our result, and the magenta short-dotted curve is the best-fit ECPL function (1) to the combined spectra between HESS, LHAASO, and this work. The figure is cited from Amenomori et al. (2022) [30].

49.5 ± 9.0 TeV with $\chi^2/\text{d.o.f.} = 10.4/8$. The flux of eHWC J1842-035 shown in the figure is our calculation from its published integral flux above 56 TeV [4] and is also consistent with our results. Therefore, the energy spectra of gamma rays in this sky region would have a cutoff or at least a break at $\simeq 50$ TeV.

4. Discussion

This section discusses the association of gamma rays from TASG J1844-038 with SNR G28.6-0.1 and PSR J1844-0346 which are located within a positional uncertainty of the TASG source.

Association with SNR G28.6-0.1 SNR G28.6-0.1 was initially specified as a radio complex G28.60-0.13 by Helfand et al. (1989) [31]. Later, the observation by ASCA detected an X-ray source ASCA J1843.8-0352 in this region and the authors claimed that the ASCA source is a supernova remnant with an age younger than 2.7 kyr accelerating high-energy electrons [32]. Ueno et al. (2003) estimated the magnetic field in the remnant at $\sim 6\,\mu$G and they suggested that electrons are accelerated by the remnant up to ~ 200 TeV [33]. In such a field strength, the energies of parent electrons for the non-thermal keV X-rays and gamma rays with $E \lesssim 100$ TeV generated through Inverse Compton Scattering (ICS) are the same order, and the extension of the X- and gamma-ray emissions should also be the same. The possible discrepancy of a 2.3 σ level between the extensions of TASG J1844-038 ($0.34° \pm 0.12°$) and of ASCA J1843.8-0352 (average radius of $4.5'$ [33]) may thus indicate that hadrons contribute to the observed gamma rays. In this case, the cutoff energy of cosmic-ray protons would be ~ 500 TeV, roughly one order of magnitude higher than the cutoff energy estimated with our combined fit.

To study the validity of the above idea, the distribution of molecular clouds, target materials for cosmic rays to produce π^0-decay gamma rays, is investigated through the analysis of the data of the ^{12}CO ($J = 1 - 0$) line emission published by the FUGIN Galactic Plane survey [34]. Ranasinghe

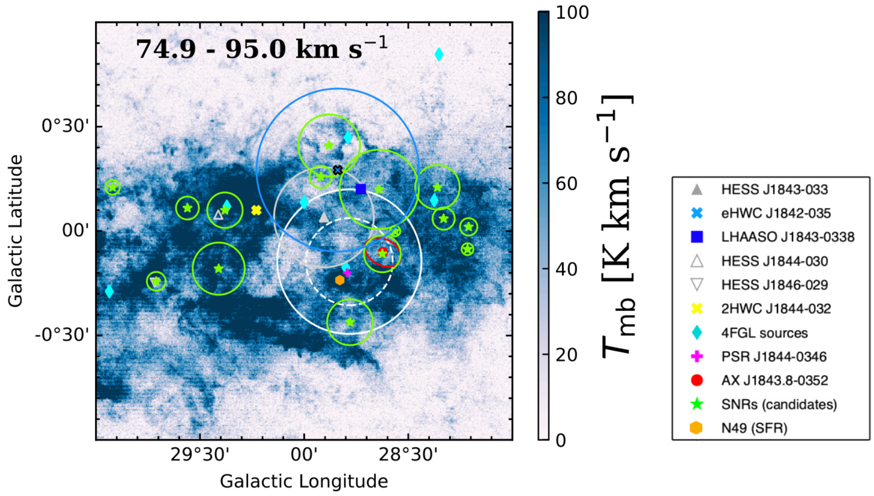

Figure 3: Brightness temperature of the ^{12}CO ($J = 1 - 0$) line emission. The position uncertainty (see Table 1) and the extension of TASG J1844-038 are indicated by the white dashed and solid lines, respectively. The positions of nearby celestial sources listed in the legend are presented and their extensions (if they have) are shown with circles. The figure is cited from Amenomori et al. (2022) [30].

& Leahy (2018) determined the distance to the SNR as 9.6 kpc from the observation of the HI absorption spectra and the detection of molecular clouds geometrically associated with the SNR in the velocity range of $\simeq$ 86 km s^{-1} [35]. Since celestial objects in our Galaxy have the proper motions of $\simeq$ 20 km s^{-1} [36], the velocity channel is integrated with 75 – 95 km s^{-1} nearly centered at 86 km s^{-1} and the distribution of clouds is compared with the position of TASG J1844-038. The result is shown in Figure 3, where some clouds lie flat over the extension of the TASG source with a $\sim$ 50 K km s^{-1} level. Therefore, it would be possible that cosmic-ray protons accelerated up to $\sim$ 500 TeV by SNR G28.6-0.1 escape the SNR and diffuse into the ambient clouds generating π^0-decay gamma rays through the interaction with them.

Association with PSR J1844-0346 Another candidate is a gamma-ray PSR J1844-0346 (also named 4FGL J1844.4–0345 [37]), discovered by the Fermi-LAT gamma-ray telescope [14]. Its spin period, spin-down luminosity, and characteristic age are obtained as P = 113 ms, $\dot{E}$ = 4.2 × 10^{36} erg s^{-1}, τ_c = 12 kyr respectively. It is interesting to discuss the association of TeV gamma-ray emission of HESS J1843-033 with PSR J1844-0346. Assuming the pulsar's pseudo distance of 4.3 kpc for the H.E.S.S. source [38], the TeV gamma-ray flux of 1.1×10^{-11} erg cm^{-2} s^{-1} is translated into the luminosity of 2.4 $\simeq$ 10^{34} erg s^{-1} and the extension of 0.24° corresponds to $\simeq$ 18 pc [12]. These characteristics of TeV gamma rays are similar to those of TeV pulsar wind nebula [27]. The gamma rays from TASG J1844-038, whose spectrum is continuously connected, can thus be associated with the PSR in the context of the leptonic scenario where gamma rays are generated through ICS off the cosmic microwave background by high energy electrons accelerated by the nebula. In that case, our spectral analysis implies that electrons are accelerated up to $\simeq$ 100 TeV. Assuming the magnetic-field strength of 3 μG in the system, the cooling time of electrons due to the synchrotron emission and ICS is roughly $\sim$ 10 kyr [39], similar order to τ_c of the PSR. The diffusion coefficient D of $\sim$ 100 TeV electrons can be roughly estimated with a simple formula of $2\sqrt{Dt_{\rm cool}} = R_{\rm ext}$ [40], where $t_{\rm cool}$ is the cooling time estimated above, and $R_{\rm ext}$ the extension of TASG J1844-038 ($\simeq$ 26 pc at the distance of 4.3 kpc). This results in $D \sim 5 \times 10^{27}\,{\rm cm^2\,s^{-1}}$, which means that the particle diffusion is suppressed more than two orders of magnitude than the Galactic average case [41]. The suppression is also observed for the Geminga PWN [42] which is recently studied as a new class of celestial object called *TeV halo* [43]. No PWN-like radio nor X-ray emission is found around PSR J1844-0346 [44], which is also a typical characteristic of TeV halos. Suppression of particle diffusion in TeV halos is theoretically studied, and the predicted suppression by about two orders of magnitude is consistent with our result [45, 46].

5. Conclusions

Data taken by the Tibet air shower array are analyzed to investigate gamma rays from the sky region of HESS J1843-033. A new gamma-ray source TASG J1844-038 is detected with a 6.2 σ level and its position is consistent with nearby gamma-ray sources (see Table 1). The extension is estimated at $0.34^\circ \pm 0.12^\circ$, also consistent with those of the H.E.S.S. and eHWC sources. The energy spectrum is measured between 25 and 130 TeV and can be fitted with a simple PL function of $dN/dE = (9.70 \pm 1.89) \times 10^{-16} (E/40\,{\rm TeV})^{-3.26\pm0.30}\,{\rm TeV^{-1}\,cm^{-2}\,s^{-1}}$. The modeling of the combined spectra between TASG J1844-038, HESS J1843-033, and LHAASO J1843-0338 implies a cutoff at 49.5 ± 9.0 TeV in the spectrum of gamma rays from this sky region. The associations of TASG J1844-038 with SNR G28.6-0.1 and PSR J1844-0346 are discussed, both leading to fascinating scenarios of cosmic-ray proton acceleration in the SNR up to $\sim$ 500 TeV and the slow diffusion of high-energy electrons in a TeV halo. However, our discussion does not account for the complex morphology of HESS J1843-033, which would require detailed theoretical modeling. Also, associations with SNR candidates discovered by the THOR survey [13] and the star forming region N49 [47] (see Figure 3) should be examined in the future.

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