HESS Observations of the Galactic Center Region and Their Possible Dark Matter Interpretation

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The detection of γ rays from the source HESS J1745-290 in the Galactic Center (GC) region with the High Energy Spectroscopic System (HESS) array of Cherenkov telescopes in 2004 is presented. After subtraction of the diffuse γ-ray emission from the GC ridge, the source is compatible with a point source with spatial extent less than $1.2'$(stat) (95% C.L.). The measured energy spectrum above 160 GeV is compatible with a power law with photon index of 2.25 ± 0.04(stat) $\pm$ 0.10(syst) and no significant flux variation is detected. It is finally found that the bulk of the very high energy emission must have non-dark-matter origin.

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Introduction.—Recently, the CANGAROO [1], VERITAS [2], HESS [3], and MAGIC [4] collaborations have reported the detection of very high energy (VHE) γ rays in the TeV energy range from the direction of the Galactic Center (GC). The nature of this source is still unknown. The main astrophysical explanations are based on particle acceleration in the region of the Sgr A East supernova remnant [5], in the vicinity of the supermassive black hole Sgr A* located at the center of our galaxy [6,7], or in a recently detected plerion [8]. Another widely discussed possibility concerns γ-ray emission from annihilation of dark-matter (DM) particles [9].

Cosmological simulations of hierarchical structure formation [10,11] predict that the DM particles form large scale structures in the Universe, and especially halos with a pronounced density cusp located at their center. Galaxies are predicted to be embedded in such DM halos. Particle physics and cosmology experiments constrain some characteristics of the new particles [12]: the new particles should be massive ($\geq$ some GeV) and have weak interactions with ordinary matter of the order of the electroweak cross sections.

Extensions of the standard model of particle physics provide new particle candidates consistent with cosmological DM and are of main interest to solve both issues. These models include supersymmetric theories [e.g., the minimal supersymmetric standard model (MSSM) [13] or the anomaly mediated supersymmetry breaking (AMSB) [14]] or Kaluza-Klein (KK) scenarios with extra dimensions [15]. All DM particle candidates have some common properties that can be used to detect them indirectly, since their annihilation may give rise not only to γ rays but also to neutrinos and cosmic rays. Their annihilation rate is proportional to the square density of DM. It is thus enhanced in the dense DM regions at the center of DM halos. Cuspy halos may therefore provide detectable fluxes of VHE γ rays (see [12] and references therein). The centers of galaxies are indeed good candidates for indirect DM detection, the closest candidate being the center of the Milky Way. The γ-ray energy spectrum generated by DM annihilation is characterized by a continuum ranging up to the mass of the DM particle, and possibly faint γ-ray lines provided by two-body final states [9,13].

For annihilation of DM particles of mass m_{DM} accumulated in a spherical halo of mass density profile $\rho(r)$ and particle density profile $\rho(r)/m_{\mathrm{DM}}$, the γ-ray flux $F(E)$ is proportional to the line-of-sight-integrated squared particle density, multiplied by the velocity-weighted annihilation cross section $\langle\sigma v\rangle$ and the number of photons dN_γ/dE generated per annihilation event [16]. $F(E)$ can be factored into a term J depending on the halo parameters and a term depending on the particle physics model:

$$F(E) = F_0 \frac{dN_\gamma}{dE} \frac{\langle\sigma v\rangle}{3\times 10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}} \left(\frac{1\ \mathrm{TeV}}{m_{\mathrm{DM}}}\right)^2 \bar{J}(\Delta\Omega)\Delta\Omega,$$

with $F_0 = 2.8\times 10^{-12}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. $\bar{J}(\Delta\Omega)$ denotes the average of J over the solid angle $\Delta\Omega$ corresponding to the angular resolution of the instrument, normalized to the local DM density 0.3 $\mathrm{GeV\,cm^{-3}}$:

$$J = \frac{1}{8.5\ \mathrm{kpc}} \left(\frac{1}{0.3\ \mathrm{GeV\,cm^{-3}}}\right)^2 \int_{\ell=0}^{\infty} d\ell\, \rho^2(\ell).$$

The shape of the measured γ-ray spectrum depends only on the particle properties, embedded in the term $F(E)$, and especially on the γ-ray multiplicity dN_γ/dE. The measured angular distribution of the γ rays depends only on $\bar{J}(\Delta\Omega)$. The overall γ-ray flux depends on both terms.

Close to the GC, halo density profiles are predicted to follow a power law $\rho_H(r) \sim r^{-\alpha}$ with α between 1 [10] and 1.5 [11]. Recent N-body simulations [17] suggest that α could monotonically decrease to zero towards the GC. Values of α lower than $\sim$1.2 lead to an angular distribution broader than the HESS angular resolution and can thus be constrained.

In this Letter, we present results on VHE γ rays from the GC based on a data set collected in 2004 with the complete HESS array of imaging atmospheric Cherenkov telescopes (IACTs).

The HESS telescopes and the Galactic Center data set.—The High Energy Spectroscopic System (HESS) is a system of four IACTs (see [18] and references therein) located in Namibia, close to the Tropic of Capricorn. The telescopes stand at the corners of a square of 120 m side. The Cherenkov light emitted by γ-induced air showers is imaged onto cameras of 960 photomultipliers, covering a field of view of 5° in diameter. The large mirror area of 107 m^2 per telescope results in an energy threshold of 100 GeV at Zenith [18,19]. The stereoscopic imaging of air showers allows the precise reconstruction of the direction and energy of the γ rays.

The previously published HESS results on the GC [3] were based on 17 h of data recorded with the first two telescopes in 2003. Here, we report on results obtained with the full four-telescope array, using 48.7 h (live time) of data collected between 30 March 2004 and 4 September 2004. The full array provides higher detection rates than the 2003 data, as well as improved background rejection and angular resolution. The bulk of the data (33.5 h) was obtained in "wobble mode," where the source region is displaced by typically $\pm$0.7° from the optical axis of the system. An additional 15.2 h data set was obtained from the Galactic plane survey [20], within 2° of Sgr A*.

Two different techniques for calibration and image analysis were applied [18,21] and give identical results. Both methods provide a typical energy resolution of 15% and an angular resolution of 0.1° above the analysis energy threshold. The results described in this Letter are derived using the second technique.

TeV γ rays from the direction of the Galactic Center.—The data show an excess of 1863 γ events from HESS J1745-290 within 0.1° from the GC (see Fig. 1). This excess is detected on top of a hadronic background of 1698 events, with a significance of 37.9 standard deviation above background, calculated according to [22].

Diffuse γ-ray emission extended along the galactic plane has been discovered in these data and was reported elsewhere [23]. It was shown that this emission likely originates in cosmic-ray interactions with giant molecular clouds and is thus proportional to the density of cosmic

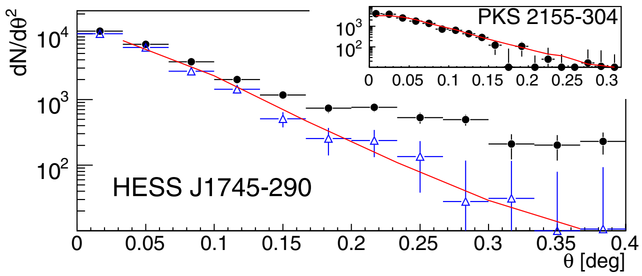

FIG. 1 (color online). Background-subtracted distribution of the angle θ between the γ-ray direction and the position of Sgr A*. Circles: all detected γ-rays events. Open triangles: central object after subtraction of the γ-ray diffuse emission model (see text). Line: calculated PSF normalized to the number of γ rays within 0.1° after subtraction is also shown. The distribution of events after subtraction matches the calculated PSF, while the initial distribution shows a significant tail. The variation of the PSF related to the source energy spectrum, zenith angle, and offset position in the field of view are taken into account. Inset: same distribution for the pointlike source PKS 2155-304 [38]. The calculated PSF (line) also matches the data. From a $dN/d\theta$ excess distribution, the y values have been divided by 2θ (θ being the bin center).

rays and of target material. To study the shape and position of HESS J1745-290, the diffuse emission has been modeled assuming a perfect correlation with the molecular cloud density from carbon-sulfur data [24]. Cosmic-ray density was assumed to have a Gaussian dependence on distance to the GC with scale $\sigma = 0.8°$. The resulting emission model has been smeared with the HESS PSF (point spread function, approximately Gaussian with a 68% containment radius of 0.1°). The HESS central source has been fitted as a superposition of the diffuse component and either a pointlike source, a Gaussian source or a DM halo shape. Likelihood fits of these different models to the γ-ray count map within a radius of 0.5° of Sgr A* were made with the flux normalization of the diffuse emission model as a free parameter. Assuming a point source for HESS J1745-290, folded with the HESS PSF, the best fit location of the source is ($\ell = 359°56'33.3'' \pm 9.7''$, $b = -0°2'40.6'' \pm 10''$) in Galactic coordinates or ($\alpha = 17^{h}45^{m}39.44^{s} \pm 0.6^{s}$, $\delta = -29d00'30.3'' \pm 9.7''$) in equatorial coordinates (J2000.0), within $7'' \pm 14''_{\rm stat} \pm 28''_{\rm syst}$ from the putative supermassive black hole Sgr A*. Improvements in the pointing accuracy may allow the systematic errors to be reduced in the future. No remaining contribution is found in the γ-ray map after subtraction of the fitted emission, indicating that this model is consistent with the data. The distribution of the angle θ between the γ-ray direction and the position of Sgr A* after subtraction of the fitted diffuse emission is shown in Fig. 1 and is consistent with the HESS PSF. The diffuse emission is found to contribute to 16% of the total signal of HESS J1745-290 within 0.1°. Assuming a azimuthally symmetric Gaussian brightness distribution centered on the best fit position given above, folded by the HESS PSF, an upper limit on the source size of 1.2′ (95% C.L.) was derived (including statistical errors only).

The compatibility of the spatial extension of HESS J1745-290 with a DM halo centered on Sgr A* and with density following $\rho(r) \propto r^{-\alpha}$ was also tested. Different values of the logarithmic slope α were assumed. The diffuse component and the DM halo were both folded with the HESS PSF. Leaving both normalizations free, the fit likelihood is compared to the pointlike source hypothesis discussed above in order to derive a lower limit on the slope α of 1.2 (95% C.L.).

The spectral energy distribution (SED) of γ rays $F(E)$ of the GC source is determined using an 0.1° integration radius and assuming a point source. As the flux contamination of the diffuse emission (16%) is of the same order as flux systematic errors, it is not subtracted in this analysis. Moreover, as the shape of the diffuse emission spectrum is compatible with that of the central source [23], the measured spectral shape is not altered. The SED is shown in Fig. 2 (together with the spectrum derived from the HESS 2003 data). Although a γ-ray excess is seen at energies as low as 100 GeV, the spectrum shown is calculated only above 160 GeV to eliminate systematic errors arising from an energy reconstruction bias close to threshold. Over the energy range 160 GeV–30 TeV the energy spectrum can be characterized by a power law $F(E) \sim E^{-\Gamma}$ with $\Gamma = 2.25 \pm 0.04({\rm stat}) \pm 0.10({\rm syst})$ (with a fit probability of 39%). The 2003 and 2004 spectra are consistent in shape and normalization, with an integral flux above 1 TeV of $[1.87 \pm 0.10({\rm stat}) \pm 0.30({\rm syst})] \times 10^{-12}\ {\rm cm}^{-2}\,{\rm s}^{-1}$. There is no evidence for a cutoff in the spectrum and lower limits at 95% C.L. of 9 and 7 TeV are derived assuming an exponential cutoff and a sharp cutoff [25], respectively. The experimental spectrum has also been fitted as a sum of

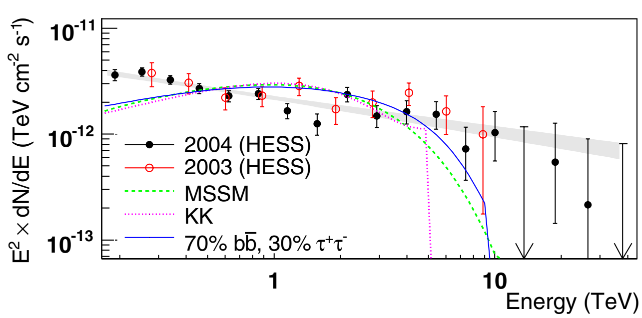

FIG. 2 (color online). Spectral energy density $E^2 \times dN/dE$ of γ rays from the GC source, for the 2004 data (solid points) and 2003 data [3] (open points). Upper limits are 95% C.L. The shaded area shows the power-law fit $dN/dE \sim E^{-\Gamma}$. The dashed line illustrates typical spectra of phenomenological MSSM DM annihilation for best fit neutralino masses of 14 TeV. The dotted line shows the distribution predicted for KK DM with a mass of 5 TeV. The solid line gives the spectrum of a 10 TeV DM particle annihilating into $\tau^+\tau^-$ (30%) and $b\bar{b}$ (70%).

a free power law and a monoenergetic γ-ray line [26] whose energy and normalization have been scanned. No indications of line emission are found.

There is no significant variation in flux between 2003 and 2004; data are consistent with a constant flux [27]. Searches for variability or flares on time scales down to 10 min did not show statistically significant deviations from the mean flux. We note that approximately 20 min of data are required for a 3 standard deviation detection of the source above background. A flare lasting for 10 min (30 min and 3 h, respectively) and with a sevenfold (fourfold and twofold, respectively) increase over the quiescent flux would be detected at the 99% C.L. Data were also analyzed for periodic or quasiperiodic variations on scales between 1 mHz and 16 μHz, using the Lomb-Scargle method [28]. Again, no statistically significant periodicity was found. However, if the VHE emission is associated with Sgr A* and given its typical rate of x-ray flares of 1.2 per 24 h [29], the 48.7 h of HESS data may simply not contain a flare event.

Dark-matter interpretation.—The location of the TeV γ-ray signal and its temporal stability are consistent with a DM annihilation signal from a halo centered on Sgr A*.

In a first step, it is assumed that all γ rays from HESS J1745-290 are due to DM annihilations. The hypothetical DM halo centered on Sgr A* was found in the previous section to be very cuspy, with a logarithmic slope α higher than 1.2. This value is consistent with the DM halo shapes predicted by some structure formation simulations. The energy spectrum provides another crucial test concerning a possible DM origin for the detected VHE emission. The extension of the spectrum beyond 10 TeV requires masses of DM particles which are uncomfortably large MSSM. The annihilation spectra of phenomenological MSSM neutralinos depend on the gaugino-Higgsino mixing, but all exhibit a curved spectrum, which in a $E^2 dN/dE$ representation rises for $E \ll m_{\mathrm{DM}}$, plateaus at $E/m_{\mathrm{DM}} \approx 0.01$–$0.1$, and falls off approaching m_{DM}. AMSB models lead to similar spectra. Such a spectral shape is inconsistent with the measured power law as seen in Fig. 2. HESS data from 2003, with restricted energy range and lower statistics, were still marginally consistent with DM spectra [30], but it appears impossible to generate a power law extending over two decades from the quark and gluon fragmentation spectra of neutralino decays, also considering radiative effects [31]. As an alternative scenario, mixed $\tau^+\tau^-$, $b\bar{b}$ final states have been proposed [32], with DM masses in the 6–30 TeV range, generating a flatter spectrum. Nonminimal supersymmetry models can be constructed which allow such decay branching ratios, combined with neutralino masses of tens of TeV. KK DM discussed in [33] also give harder spectra. PYTHIA 6.225 [34] was used to compute the contributions from all annihilation channels [35]. However, all the tested model spectra still deviate significantly from the observed power-law spectrum as shown in Fig. 2.

On the other hand, if the bulk of the VHE emission has non-DM origin, there is still the possibility of a DM signal hidden under an astrophysical spectrum. To search for such a contribution, we fitted the experimental spectrum as the sum of a power law with free normalization and index, and a MSSM (or KK) spectrum. Leaving the normalization of the DM signal free, the range of m_{DM} is scanned. For the MSSM, annihilation spectra $dN_\gamma/dE = (N_0/m_\chi) \times (E/m_\chi)^{-\Gamma} \exp(-cE/m_\chi)$ are used with three different sets of parameters, one approximating the average annihilation spectrum $[(N_0, \Gamma, c) = (0.081, 2.31, 4.88)]$ and the other two $[(N_0, \Gamma, c) = (0.2, 1.7, 10)$ and $(0.4, 1.7, 3.5)]$ roughly encompassing the range of model spectra generated using DARKSUSY [16,36]. No significant DM component is detected with this procedure, the DM component flux upper limit being of the order of 10% of the source flux. Assuming a Navarro-Frenk-White profile, 99% C.L. upper limits on the velocity-weighted annihilation cross section $\langle\sigma v\rangle$ are of the order of 10^{-24}–10^{-23} cm^3 s^{-1}, above the predicted values of the order of 3×10^{-26} cm^3 s^{-1}. These limits can vary by plus or minus 3 orders of magnitude if one assumes other DM halo shapes. In the case of adiabatic compression of DM due to the infall of baryons to the GC, the flux could be boosted up to a factor 1000 [37]. The HESS data might then start to exclude some $\langle\sigma v\rangle$ values.

In conclusion, the power-law energy spectrum of the source HESS J1745-290 measured using the HESS telescopes show that the observed VHE γ-ray emission is not compatible with the most conventional DM particle annihilation scenarios. It is thus likely that the bulk of the emission is provided by astrophysical non-DM processes. However, due to high density of candidate objects for nonthermal emission within the source region the nature of the source is not clear.

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