Spectral analysis of the Galactic Center emission at very-high-energy gamma-rays with H.E.S.S

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Abstract: The Galactic Centre region has been observed by the complete H.E.S.S.-I array of ground-based Cherenkov telescopes since 2004 leading to the detection of the very-high-energy (VHE, E $\geq$ 100 GeV) gamma-ray source HESS J1745-290 coincident in position with the supermassive black hole Sgr A*. A TeV gamma-ray diffuse emision has been detected along the Galactic ridge, very likely to be related to cosmic-ray interactions in giant molecular clouds of the Central Molecular Zone. We report here on a spectral morphology study of the inner 50 pc of the Galactic Centre region using the full data set of 2004-2012 observations . The contamination from diffuse emission to HESS J1745-290 is subtracted which allows to recover the intrinsic spectrum of the central source. The intrinsic source spectrum is well described by a power-law spectrum with an exponential energy cut-off at $\sim$ 7 TeV.

Keywords: Galactic Center, gamma rays, HESS J1745-290, Diffuse emission

1 Introduction

An impressive observational activity developed in the Galactic Center (GC) region since the detection of a gamma-ray emission from the direction of the Galactic Center by the EGRET satellite (3EG J1746-2852, [1]). Observations with imaging atmospheric Cherenkov telescopes soon after gave rise to the detection of an emission in the very-high-energy (VHE, E $>$ 100 GeV) gamma-ray regime by the CANGAROO [2], VERITAS [3], H.E.S.S. [4] and MAGIC [5]. The *Fermi-LAT* satellite then detected a central source, 1FGL J1745.6-2900, coincident in position with Sgr A* [6], though no firm conclusion does exist about the association of the *Fermi-LAT* source with the VHE gamma-ray source due to the presence of a strong diffuse gamma-ray emission in the same energy range. The observations of the GC region with the H.E.S.S. instrument led to the detection of a point-like source of VHE gamma-rays, HESS J1745-290, with an unprecented accuracy in the TeV energy range thanks to its location in the southern hemisphere, its wide field of view and the excellent hardware performances. While spatially coincident with the supermassive black hole Sgr A*, the position of HESS J1745-290 was still compatible with the supernova remnant Sgr A East, and the plerion G359.95-0.04, despite the angular resolution of the H.E.S.S. instrument of about $6'$. A larger exposure on the GC region revealed a ridge of diffuse emission extending along the Galactic plane for about 2° in Galactic longitude, which was found to be spatially correlated to giant molecular clouds located in the central molecular zone [7]. The strong correlation between the morphology of the diffuse gamma-ray emission and the density of molecular clouds indicates the presence of a proton accelerator in the GC region, since energetic proton interactions with the cloud material would give rise to the observed gamma-ray flux via π_0 decays. After a careful investigation of the pointing systematics of the H.E.S.S. telescopes, the systematic error on the centroid position of HESS J1745-290 emission was reduced to $13''$, allowing the exclusion of Sgr A East supernova remnant as the main counterpart of the VHE emission [8]. The very nature of this VHE central emission remains still unknown, leaving Sgr A* [9, 10], G359.95-0.04 [11, 12] and the inner 10 pc diffuse emission around Sgr A* [13] as plausible contributing sources for the observed emission. The H.E.S.S. experiment has been taking observations of the Galactic Center region for nine years with the full telescope array and the data collected by H.E.S.S. allows for the most detailed high energy gamma-ray picture reported to date of the GC region.

The paper is structured as follows. Section 2 describes the analysis of the entire available dataset of H.E.S.S. towards Sgr A* from 2004 to 2012. The diffuse TeV emission is analyzed in the close-by neighbourhood of HESS J1745-290 in section 3. The contamination of the diffuse gamma-ray emission to the central source is quantified and the intrinsic spectrum of the central source is obtained. The main results are summarized in section 5.

2 H.E.S.S. observations of the Galactic Center from 2004 to 2012

2.1 Dataset and data analysis

The H.E.S.S. (High Energy Stereoscopic System) array of Cherenkov telescopes is located in the Khomas Highlands of Namibia at an altitude of 1800 m. The phase-I system consists of four identical imaging atmospheric Cherenkov telescopes. Each of them is equipped with a tesselated mirror of a 107 m^2 surface area and a camera of 960 photomultipler tubes. The total field of view of H.E.S.S. is 5° in diameter. The H.E.S.S. instrument achieves an angular resolution at a 68% containment radius of 0.07° per gamma-ray and an energy resolution of 15% on average. The point-like source sensitivity is at the level of $2 \times 10^{-13} cm^2 s^{-1}$

above 200 GeV for a 5 σ detection in 25 hours at a mean observation zenith angle of 20° and an offset of 0.7° [14]. A fifth telescope completing the H.E.S.S.-I array started operation in 2012, but no data acquired with the five telescope array is used in what follows.

Table 1: H.E.S.S. observation campaigns towards the Galactic Center from 2004 to 2012. Here θ_z indicates the mean zenith angle of observations and T_{obs} the acceptance-corrected livetime of the H.E.S.S. observations. The number of gamma-ray excess events is calculated in a circular region of 0.1°around the nominal position of Sgr A*. The significance of the gamma-ray excess is calculated according to the method of [15]

Year	θ_z [°]	T_{obs} [h]	gamma-ray excess	Significance [σ]
2004	21.8	48.5	2075.2	53.4
2005	28.8	68.6	2594.6	60.8
2006	18.7	28.7	1056.8	38.0
2007	11.2	11.4	399.8	24.6
2008	15.3	13.2	567.0	27.3
2009	17.8	4.4	123.7	12.8
2010	10.8	8.3	294.9	21.0
2011	33.6	10.1	267.9	18.5
2012	21.4	26.8	1078.2	38.8
All	22.6	220.0	8422.7	108.1

Data are taken in *wobble mode* where the pointing direction is chosen at an alternating offset of 0.7° to 1.1° from the target position [17]. Standard quality selection is applied to the data to reject observation runs affected by bad weather conditions or poor performance instrument [17]. After the selection procedure, the data set amounts to 220 hours of live time at the nominal position of Sgr A*. The analysis technique used to select the gamma-ray events is based on a semi-analytical model of the air shower development. The observed images are compared to the predicted images with a maximum likelihood technique [14]. The background level is calculated in each position using the *Ring Background* method from an annulus region, the *OFF* region, around the center of the camera with a radius equal to the offset of observation and a width equal to the signal region, or *ON* region, radius. The *OFF* regions are chosen so that they do not neither overlap with known TeV sources nor diffuse TeV emission detected in the Galactic Center region [7]. The analysis of the whole dataset shows an excess of 8422 gamma-ray events in a circular region of 0.1° centered on Sgr A*, with a total significance of 108 σ. The energy threshold for this analysis is 140 GeV. Table 1 summarizes the observations of the Galactic Center from 2004 up to 2012 together with gamma-ray excess counts and significances given year by year and for the full dataset. The diffuse gamma-ray emission contribution to HESS J1745-290 is visible as illustrated by the distribution of the squared angular distance θ^2 of the reconstructed direction of the gamma rays from the Galactic Center on Fig. 1. For $\theta^2 \geq 0.04°$, the signal is well dominated by the diffuse emission most likely originating from hadronic cosmic-ray interactions in hydrogen clouds of the Central Molecular Zone [7].

2.2 Update of HESS J1745-290 spectrum

The spectrum of HESS J1745-290 is calculated applying a spectral reconstruction *forward-folding* method. This method is based on a maximum-likelihood procedure, comparing the energy distributions of ON and OFF events to pre-defined spectral shapes. Two spectral shapes are used in the fitting procedure, a power-law,

$$\Phi(E) = \Phi_0 \times \left(\frac{\mathrm{E}}{1\,\mathrm{TeV}}\right)^{-\Gamma}, \tag{1}$$

and a power-law with an exponential energy cut-off,

$$\Phi(E) = \Phi_0 \times \left(\frac{\mathrm{E}}{1\,\mathrm{TeV}}\right)^{-\Gamma} \times e^{-\frac{\mathrm{E}}{\mathrm{E_c}}}, \tag{2}$$

Φ_0 is the flux normalisation in TeV^{-1} cm^{-2} s^{-1}, Γ the spectral index, $\mathrm{E_c}$ the exponential cut-off energy in Eq. (2).

The spectrum is well described by a power-law with an exponential cut-off (χ^2/d.o.f. = 75.7/74), confirming the tendency found in [16]. By comparison, the spectral reconstruction with a pure power-law gives a χ^2/d.o.f. = 110.2/75, thus strongly favoring a spectrum with an exponential energy cut-off. The power-law fit with an exponential energy cut-off yields a spectral index of $\Gamma = 2.14 \pm 0.03_{\mathrm{stat}} \pm 0.10_{\mathrm{syst}}$, with an exponential cut-off at $\mathrm{E_c} = (10.7 \pm 2.0_{\mathrm{stat}} \pm 1.8_{\mathrm{syst}})$ TeV and $\Phi_0 = (2.55 \pm 0.04_{\mathrm{stat}} \pm 0.38_{\mathrm{syst}}) \times 10^{-12}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{TeV}^{-1}$. The systematic errors are 5 % for the spectral index, 17 % for the cut-off energy and 15 % for the integrated flux, following the results presented in [16]. The values of spectral parameters found with the full data set are in good agreement with the published 2006 and 2009 spectra. To investigate the possible evolution of the spectral parameters with the cumulated exposition time, the spectral analysis has been performed using for sub-data sets *i.e.* from 2004-2008, 2004-2009, 2004-2010 and 2004-2011 data sets, respectively. Table 2 summarizes the spectral parameters for a power-law spectrum with exponential energy cut-off for the different data sets. The increase in the number of detected gamma-ray excess due to the additional observations since 2006, especially at very high energies, allows for a more accurate measurement of the spectrum shape in the TeV energy range.

3 Diffuse emission contamination to the HESS J1745-290 spectrum

3.1 Diffuse emission spectrum in the inner 50 pc from the Galactic Centre

Although HESS J1745-290 is likely to be related to the supermassive black hole and/or the plerion G359.95-0.04, part of the gamma rays definitely comes from the contribution of the diffuse emission. The determination of the contamination of the diffuse emission spectrum to the HESS J1745-290 spectrum proceeds in two disctinct steps: first, the spectral shape needs to be determined and secondly the amplitude of this contribution. The gamma-ray energy spectrum of the diffuse emission is calculated in a target in the vicinity of the HESS J1745-290. The ON region is defined as an annulus centered on the Sgr A* position with an inner radius r_{in} = 0.1° and an outer radius r_{out} = 0.4°.

Table 2: Values of the spectral parameters of the HESS J1745-290 energy spectrum for different datasets with their respective statistical errors. The spectrum is fitted with a power-law with index Γ and an exponential energy cut-off at the energy E_c. Errors quoted here refer to 1 σ statistical errors only.

Data set	Φ_0 $[10^{-12}$ TeV^{-1} cm^{-2} s$^{-1}]$	Γ	E_c [TeV]	$\Phi(\geq 1\text{TeV})$ $[10^{-12}$ cm^{-2} s$^{-1}]$	χ^2/d.o.f.
2004-2008	2.61 ± 0.04	2.14 ± 0.03	10.8 ± 2.2	1.74 ± 0.07	62.7/61
2004-2009	2.59 ± 0.04	2.14 ± 0.03	10.8 ± 2.2	1.72 ± 0.07	70.3/66
2004-2010	2.58 ± 0.04	2.14 ± 0.03	10.5 ± 2.0	1.71 ± 0.06	72.5/68
2004-2011	2.53 ± 0.04	2.15 ± 0.03	11.3 ± 2.4	1.69 ± 0.06	71.8/68
All	2.55 ± 0.04	2.14 ± 0.03	10.7 ± 2.0	1.69 ± 0.06	75.7/74

Assuming that the diffuse emission has an azimuthal symmetry along the Galactic plane, gamma rays with a similar energy spectrum should be contributing as foreground and background to the intrinsic HESS J1745-290 spectrum.

The data analysis is performed with the same technique for the gamma-ray event selection as for the HESS J1745-290 analysis, and the background level is determined by the *Multiple-Off* technique, using OFF regions placed around the observation position at the same off-set as the ON region. An excess of more than 10146 gamma rays is found above 140 GeV in the ON region with a total significance of 70.6 σ. The energy spectrum is then fitted by a power-law distribution, and an index of $\Gamma = 2.48 \pm 0.02_{stat} \pm 0.10_{syst}$ is found.

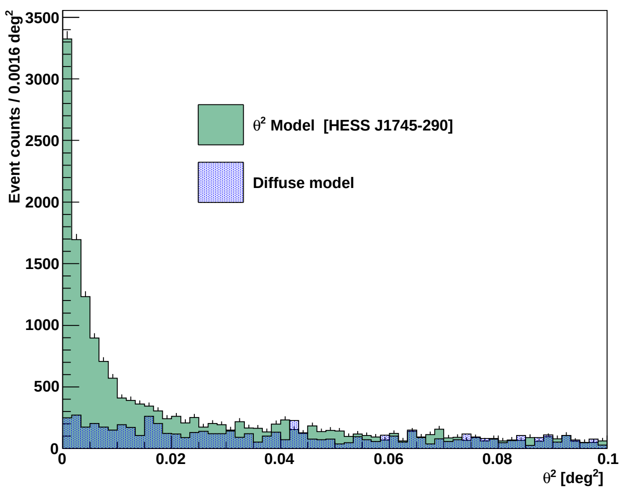

Figure 1: Angular distribution of gamma-ray events plotted as function of θ^2 for HESS J1745-290 (green histogram). The angular distribution of gamma-ray events predicted by the diffuse model (blue histogram) is shown. The model was renormalised in order to match the observed number of gamma-rays for $\theta^2 \geq 0.04$ deg^2. The ON source region corresponds to squared angular distances $\theta^2 \leq 0.01$ deg^2.

3.2 Amplitude of the diffuse emission contamination

A simple method to estimate the amplitude of the diffuse emission contribution to HESS J1745-290 is by fitting θ^2 the events distribution, shown in Fig. 1, under the assumption of a central point-like source plus a linear component to account for the diffuse emission. Extending the linear part under the central source gives a first estimation of the diffuse emission contamination to HESS J1745-290, which by this procedure is found to be about 11%. However a more accurate determination can be done by modelling the diffuse emission as coming from the interaction of hadronic cosmic-rays, accelerated in the vicinity of the Galactic Center, with the interstellar material of the Central Molecular Zone. Because of the close correlation between the gamma-ray emission and the density of interstellar material in GMCs, the gamma-ray flux is assumed to be proportional to the matter density. The latter is obtained by means of CS observations [19]. The CS map is then convoluted with the point spread function corresponding to the cuts used in the analysis presented in Section 2.1 to match the angular resolution of H.E.S.S. instrument. The normalisation of the predicted gamma-ray map is later matched to the data. Using the angular distribution of gamma-ray events shown in Fig. 1, a linear regression between the model and the observed events for squared distance $\theta^2 \geq 0.04$ deg^2 is performed to normalize the diffuse emission model. The diffuse component contamination to HESS J1745-290 then amounts to 19%. The linear regression error at 1σ level gives an uncertainty of ± 5 % for the estimate of the contamination.

3.3 Intrinsic spectrum of HESS J1745-290

The intrinsic spectrum of the central source is recovered by fitting the data assuming two spectral components. The first component is set to the expected diffuse emission spectrum under the central source, for which the normalisation is found so that the expected number of gamma rays due to the diffuse component matches the 19% of the expected number of gamma rays due to HESS J1745-290. The expected number of gamma rays per unit of time coming from a given source is found by folding the source spectrum with the detector acceptance, obtained from the observational dataset, and integrating over all energies. The second component is assumed to have a power law with an exponential energy cut-off shape. This component is hereafter referred as to the intrinsic spectrum of the central source and is found after fitting the sum of the two components to the data. Figure 2 shows the total energy spectrum of HESS J1745-290, with the analytical form of the two components highlighted. The intrinsic central source spectrum reveals a spectral index of $2.04 \pm 0.03_{stat} \pm 0.10_{syst}$, with an energy cut-off at (7.9 $\pm 1.3_{stat}$ $\pm 1.2_{syst}$) TeV, and $\Phi_0 = (2.53 \pm 0.09_{stat} \pm 0.40_{syst}) \times 10^{-12}\,\mathrm{cm^{-2}s^{-1}TeV^{-1}}$. The total fit gives a χ^2/d.o.f. = 68.1/74. Gamma rays from the diffuse emission dominate HESS J1745-290 spectrum at energies above $\sim$ 25 TeV.

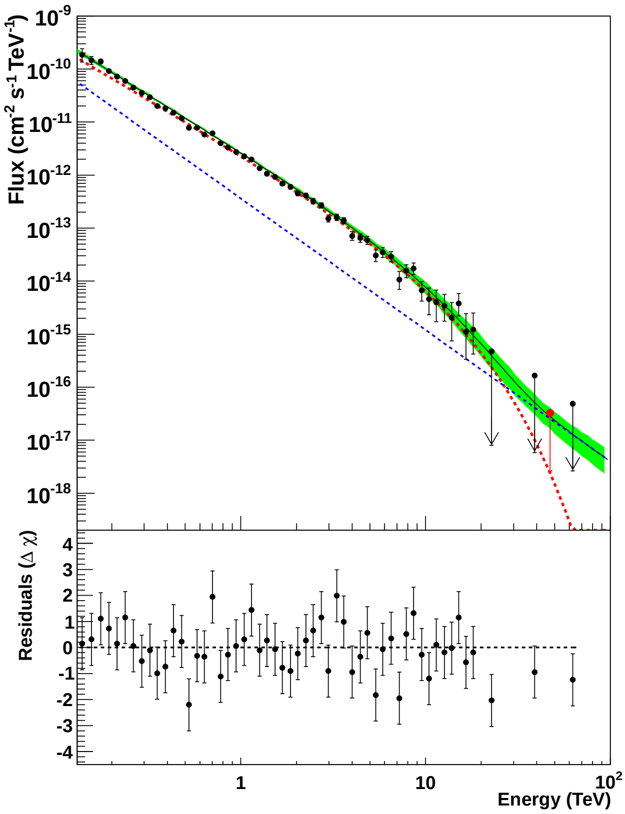

Figure 2: Top panel : The green region correspond to the 1 σ contour for the best-fit with the sum of two components, a power law with parameters completely fixed and a power law with an exponential energy cut-off. The HESS J1745-290 spectrum (black line) is the sum of the diffuse spectrum (blue line) and the central gamma-ray source (red line). The data points are obtained with the *forward-folding* method. A 95% C. L. upper limit on the intrinsic central gamma-ray source flux is also plotted (red point) . Bottom panel : The residuals of the fit ($N_{\gamma,obs}$ - $N_{\gamma,th}$)/$\sigma_{\gamma,obs}$. It is well centered on 0, which indicates the good quality of the fit.

4 Summary

A study of the spectral morphology of the inner 50 pc of the Galactic Center region using the whole H.E.S.S. data set from 2004 to 2012 is presented. The energy spectrum of the central HESS J1745-290 still shows a clear deviation from pure power-law spectrum, with an energy cut-off at $(10.7 \pm 2.0_{stat} \pm 1.8_{syst})$ TeV. The determination of the energy spectrum of the diffuse emission around the central source is found to follow a power-law distribution with an spectral index of $2.48 \pm 0.02 \pm 0.10_{syst}$. The contamination of the diffuse emission to HESS J1745-290 is calculated through a model of hadronic interaction in the central molecular clouds. The contribution is found to account for 19% $\pm$ 5% of the total signal of HESS J1745-290. The intrinsic spectrum of the central source is found after a spectral subtraction of the diffuse component under the HESS J1745-290 signal, revealing a stronger energy cut-off at (7.9 $\pm 1.37.78_{stat}$ $\pm 1.2_{syst}$) TeV. Additionally gamma rays from the diffuse emission are predicted to dominate the full HESS J1745-290 spectrum at energies above 25 TeV.

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