Spectrum and variability of the Galactic Center VHE γ-ray source HESS J1745-290

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***Abstract*. The center of our galaxy harbours an unidentified very high energy (VHE) γ-ray source which coincides spatially with the super-massive black hole (SMBH) Sgr A*. The multi-wavelength emission of Sgr A* has been firmly established for many years with variabilities in radio, infrared (IR) and X-rays. The VHE γ-ray source HESS J1745-290 has been monitored by the H.E.S.S. collaboration since it was first detected in 2004 for a precise study of its energy spectrum and time variability. In this paper are presented the latest results on the HESS J1745-290 spectrum and variability, obtained with a data set that comprises data from the 2004, 2005 and 2006 observation campaigns.**

***Keywords*: gamma-ray astronomy, galactic center, spectrum and variability**

I. Introduction

The center of the Milky-Way is the most violent and active region in our Galaxy. Precise data have been obtained toward this region at radio, IR and X-rays energies and have revealed a complicated morphology with various astrophysical objects. VHE γ-ray emission from the direction of the Galactic Center (GC) was also reported by several ground-based Cherenkov instruments [1], [2], [3], [4]. A recent deep exposure by H.E.S.S. revealed the existence of a diffuse emission along the Galatic plane [5], on top of the VHE emission of the GC source HESS J1745-290 and the pulsar wind nebulae (PWN) G0.9+0.1 [6]. Despite recent improvements in the H.E.S.S. pointing accuracy and source position determination [7], a firm identification of the HESS J1745-290 GC source is difficult. Indeed, various sources of non-thermal radiation lie within the H.E.S.S. 0.1° angular resolution and may be VHE γ-ray emitters. Among these are the SMBH Sgr A*, the supernovae remnant (SNR) Sgr A East [8] and the PWN G359.95-0.04 [9].
A solution to distinguish between possible counterparts might be the study the energy spectrum and time variability of the VHE γ-ray source. For example, the varying non-thermal IR and X-ray emission of Sgr A* points to particle acceleration near the SMBH horizon, which may be closely related to the detected VHE γ-ray emission. The spectral and time variability features of the HESS J1745-290 source can then bring new insights into the origin of the TeV emission in the GC region. This paper reports on the latest results on the energy spectrum and time variability of the HESS J1745-290 γ-ray source.

II. H.E.S.S. observations of the Galactic Center region

The previously published results on the HESS J1745-290 source spectrum and time variability are based on a 50 h exposure data sample collected in 2004 [10]. The HESS J1745-290 2004 energy spectrum was found to follow a power-law $\mathrm{dN/dE_\gamma} \propto \mathrm{E_\gamma^{-\Gamma}}$ with a spectral index $\Gamma = 2.25 \pm 0.04_{\rm stat} \pm 0.1_{\rm syst}$. No deviation from a pure power-law was observed and the source was found to be stable on timescales ranging from a few min to a year.
The results reported here were derived with further data recorded during the 2005 and 2006 observation campaigns [18], [19]. The total good-quality exposure of the data set is 92.9 h. Most of the data were taken in "wobble mode", where the telescope pointing is typically shifted by ± 0.7° from the nominal target position. The remaining data were taken at various offset angles, within 1.5° from the position of Sgr A*. The zenith angle distribution of the observations ranges from 0° up to 70°, with a mean value of 23°.

Data were analysed using the combination of two techniques for the γ-rays selection and reconstruction. The first technique computes the "Hillas geometrical moments" of the shower image [11] and the second one is based on a semi-analytical model of showers, which predicts the expected intensity in each pixel of the camera [12]. Both analysis techniques provide an energy resolution of 15-20% with an angular resolution better than 0.1° above the analysis energy threshold. The data show an excess of 4185 γ-ray events above the background within a 0.11° radius region centered on the GC, accompanied by diffuse emission along the Galactic plane. The total significance of the excess, calculated according to the method of Li & Ma [13], is 60.7 standard deviations above the background. The contamination of the diffuse emission is estimated to be less than 13% ± 1% within the 0.11° radius region. The diffuse emission was not subtracted in the HESS J1745-290 energy spectrum reconstruction and time variability

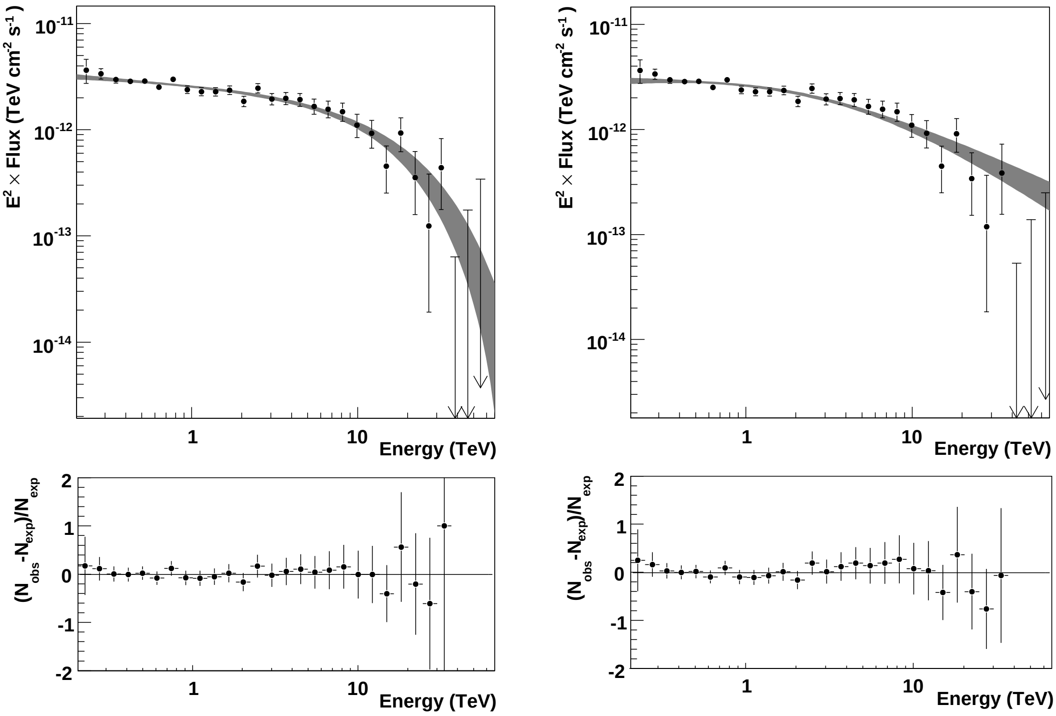

Fig. 1. HESS J1745−290 spectra derived for the whole HESS GC dataset covering the three years 2004, 2005 and 2006. The shaded areas are the 1σ confidence intervals for the power law with an exponential cut-off fit (left) and the broken power law fit (right). The last points represent 95% C.L upper limits on the flux. The fit residuals corresponding to the respective fits are shown on the lower panels.

studies, since its spectral features would not influence the results (a simple power-law with the same spectral index as the central source) [5].

III. Energy spectrum of HESS J1745-290

The data taken in 2004, 2005 and 2006 were compared to the folding of three distributions with the detector response: a power law (Eq. 1), a power law with a high energy exponential cut-off (Eq. 2) and a smoothed broken power law (Eq. 3):

$$\frac{dN}{dE} = \Phi_0 \times \left(\frac{E}{1\mathrm{TeV}}\right)^{-\Gamma} \quad (1)$$

$$\frac{dN}{dE} = \Phi_0 \times \left(\frac{E}{1\mathrm{TeV}}\right)^{-\Gamma} \times e^{-(\frac{E}{E_{\mathrm{cut}}})} \quad (2)$$

$$\frac{dN}{dE} = \Phi_0 \times \left(\frac{E}{1\mathrm{TeV}}\right)^{-\Gamma_1} \times \frac{1}{\left(1+\left(\frac{E}{E_{\mathrm{break}}}\right)^{(\Gamma_2-\Gamma_1)}\right)} \quad (3)$$

where Φ_0 is the flux normalisation in TeV^{-1} cm^{-2} s^{-1}, Γ_i the spectral indices. E_{cut} is the cut-off energy in Eq. 2, and E_{break} is the break energy in Eq. 3.

The measured spectrum for the whole three-year dataset ranges from 160 GeV, the energy threshold of the analysis, to 70 TeV (Fig. 2). For the first time, with additional statistics, a deviation from a pure power law starts to be visible. The spectrum is well described by either Eq. 2 (equivalent χ^2 of 23/26 d.o.f.) or Eq. 3 (equivalent χ^2 of 20/19 d.o.f.). Fig. 2 shows the HESS J1745−290 spectra with fits to Eq. 2 and Eq. 3. The power law with an exponential cut-off fit yields Φ_0 = (2.55 ± 0.06_{stat} ± 0.40_{syst}) × 10^{-12} TeV^{-1} cm^{-2} s^{-1}, Γ = 2.10 ± 0.04_{stat} ± 0.10_{syst}, a cut-off energy E_{cut} = (15.7 ± 3.4_{stat} ± 2.5_{syst}) TeV and an integrated flux above 1 TeV of (1.99 ± 0.09_{stat} ± 0.40_{syst}) × 10^{-12}cm^{-2} s^{-1}. The broken power law fit yields Φ_0 = (2.57 ± 0.07_{stat} ± 0.40_{syst}) × 10^{-12} TeV^{-1} cm^{-2} s^{-1}, Γ_1 = 2.02 ± 0.08_{stat} ± 0.10_{syst}, Γ_2 = 2.63 ± 0.14_{stat} ± 0.10_{syst}, a break energy E_{break} = (2.57 ± 0.19_{stat} ± 0.44_{syst}) TeV and an integrated flux above 1 TeV of (1.98 ± 0.38_{stat} ± 0.40_{syst}) × 10^{-12}cm^{-2} s^{-1}. By comparison, a power law spectrum gives a worse equivalent χ^2 of 64/27 d.o.f. and yields a flux normalisation of (2.40 ± 0.05_{stat} ± 0.40_{syst}) × 10^{-12} TeV^{-1} cm^{-2} s^{-1}, a spectral index of 2.29 ± 0.02_{stat} ± 0.10_{syst} with an integrated flux above 1 TeV of (1.87 ± 0.05_{stat} ± 0.40_{syst}) × 10^{-12}cm^{-2} s^{-1}. The effect of introducing a high cut-off energy in the power law spectrum does not change the integrated flux by more than 10%, less than systematic errors. Integrated fluxes found either with a power law with an exponential cut-off shape or a smoothed broken power law one are consistent with the values given in the previous published H.E.S.S. analysis [10].

IV. Search for time variability

As mentioned in the introduction, Sgr A* is a highly variable source with daily flares detected in IR and X-rays. Quasi periodic oscillations (QPOs) were also reported in these wavebands [14], [15], [16]. However, the validity of the detection of the IR periods has

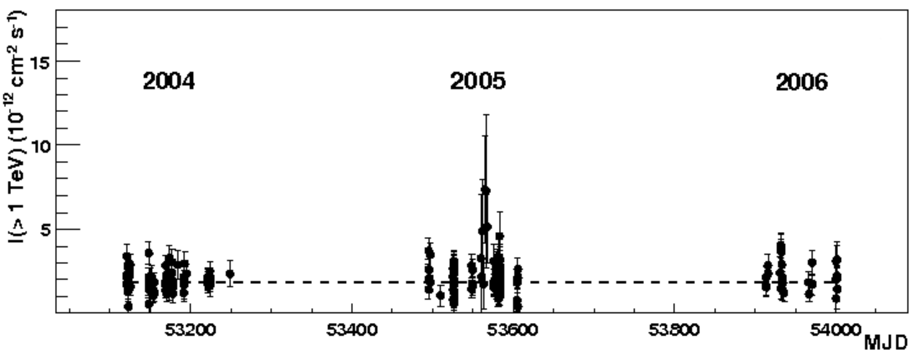

Fig. 2. Run by run light curve of HESS J1745−290. The 28 min interval integrated fluxes of HESS J1745-290 are plotted for the 2004, 2005 and 2006 datasets. The dashed line shows the best fit to a constant.

recently been disputed by observations of the Keck II telescope (see ([17]) for references). In this section, the "run by run" and "night by night" light curves (LCs) are used to search for any variablility in the HESS J1745-290 source activity.

A. *Light curve and flare sensitivity*

The "run by run" integrated flux LC of the GC covering the 2004, 2005 and 2006 observation seasons is displayed on Fig. 2. Each point represents the integrated flux above 1 TeV computed for a 28 min time interval, corresponding to a run of data. The fit of a constant to the data taken over the whole three years gives a χ^2 of 233/216 d.o.f. and does not reveal any variability on time scales longer than 28 min. Given the non detection of any flaring activity, a flare sensitivity study has been carried out by adding a fake Gaussian to the LC. The amplitude of the Gaussian defines the TeV flux increase and its variance defines the flare duration [18], [19]. It was found that an increase of the flux by at least a factor of two is necessary to detect flares of hours time scale at the 3σ level. An increase of the γ-ray flux of a factor of 2 or greater was excluded at a confidence level of 99% during a Chandra flare night by the H.E.S.S. collaboration [20], which is fully consistent with this result.

B. *Search for QPOs*

Four oscillation frequencies ranging from 100 s to 2250 s have been observed in the X-ray LC of SgrA* [21]. These frequencies are likely to correspond to gravitationnal cyclic modes associated with the accretion disk of Sgr A*. The occurence of these frequencies have been searched for in the HESS J1745-290 data set.
First, the coherence time of the disk oscillations was assumed to be less than 28 min, in which case Rayleigh tests [22] on photon time arrival distributions for continuous observations of 28 min were performed. The Rayleigh power averaged over 2004-2006 data is shown on Fig.3 as a function of the tested frequency. The probed frequencies range from 1/28 min^{-1} to the inverse of the average time spacing between two consecutive events of 1.2 min^{-1}. The Rayleigh power is compatible with a flat function of frequency. No significant peaks are seen at the 100 s, 219 s, 700 s and 1150 s periods observed in X-rays.
In a second case, the coherence time of the disk oscillations was assumed to be of the order of a few hours. The Fourier power distribution using Lomb-Scargle periodograms [23] were computed for each night of the data set with LCs binned into 5 min points. The Fourier power averaged over the whole nights of the 2004-2006 data set is displayed on Fig.4 as a function of the frequency. The tested frequencies range from 10^{-2} min^{-1} to 0.1 min^{-1}. No significant oscillation frequencies are detected.

V. CONCLUSIONS

The new data taken in 2005 and 2006 toward the GG region with H.E.S.S. have allowed significant improvements in characterizing the HESS J1745-290 energy spectrum and variability. The measured spectrum with the 2004, 2005 and 2006 data sets exhibits a deviation from a pure power-law at high energies ($\geq$ 10 TeV), and no significant flaring activity was found in the TeV emission, in contrast to the observed flares in the Sgr A* IR and X-rays emission. Moreover, the non detection of QPOs supports the idea that the TeV emission is not correlated with the SMBH activity. Thus, the emission mechanisms responsible for the TeV emission seems not to be the same as those accounting for the radio to X-rays emission.

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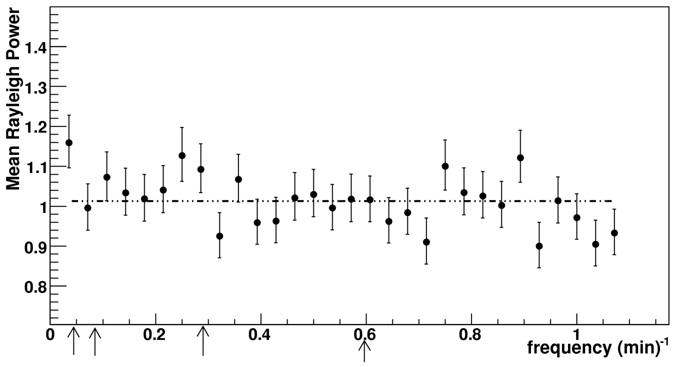

Fig. 3. Rayleigh power plotted as a function of the frequency. Rayleigh power is normalized such that a pure noise spectrum results in unit power. The dotted line shows the fit to a constant of the Rayleigh spectrum. The arrows denote the 100 s, 219 s, 700 s and 1150 s periods observed in X-rays.

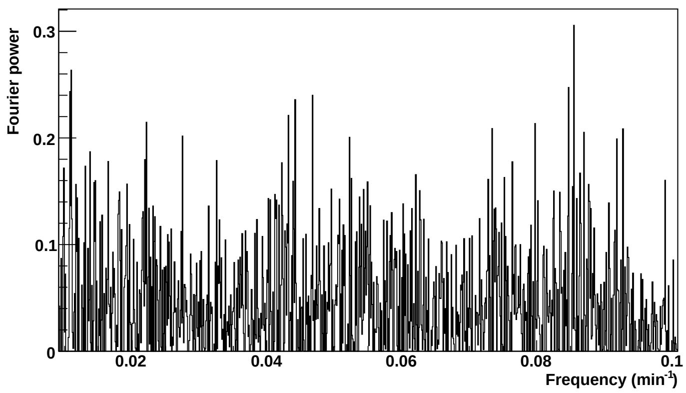

Fig. 4. [10^{-2} min^{-1} - 0.1 min^{-1}] Lomb-Scargle periodogram of the H.E.S.S. Sgr A* LC averaged over the 2004-2006 nights of observation.

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