IT'S A BLAZAR...IT'S A RADIO GALAXY... IT'S PKS 0625-354!*

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The catalogue of TeV gamma-ray emitting objects includes about 90 extragalactic sources, among which only a few belong to the class of radio galaxies or misaligned blazars. This smaller class includes PKS 0625-354, a source detected as a TeV gamma-ray emitter already in 2012. Here, we report on H.E.S.S. observations of this active galaxy performed in November 2018. The classification of the object is still a matter of debate in the context of blazar and radio-galaxy scenarios. With the recent H.E.S.S. observations, supported with multi-wavelength observations collected with *Fermi*-LAT, *Swift*-XRT, and *Swift*-UVOT, we report on the detection of TeV gamma-ray variability of the sources. Ten days of H.E.S.S. observations revealed an outburst observed on November 1 followed by a decrease in the gamma-ray flux. We report on the result of H.E.S.S. and multi-wavelength observations of PKS 0625-354. We also discuss the possible interpretation of the broadband spectral energy distribution of the source and the implication of the TeV gamma-ray variability detected.

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1. Introduction

The extragalactic sky as seen in very high energy (VHE) γ-ray energies is dominated by blazars. Only six sources in the catalogue of TeV γ-ray emitters [1] belong to the class of radio galaxies or misaligned blazars. These

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are: NGC 1275 [2], 3C 264 [3], M 87 [4], Cen A [5], IC 310 [6], and PKS 0625-354 [7] (see also Table 1 for details). However, the classification of the latter two, IC 310 and PKS 0625-354, is still a matter of debate as they reveal features that appear in both radio galaxy and blazars.

Table 1. Radio galaxies reported as VHE γ-ray emitters.

Source	Current classification	Redshift
Cen A	FR I	0.0018
M 87	FR I	0.0044
NGC 1275	FR I	0.0176
3C 264	FR I	0.0217
IC 310	unclear	0.0189
PKS 0625-354	unclear	0.0549

PKS 0625-354, known also as OH 342, is a source located in the Cluster Abell 3392 with a redshift of $z = 0.055$ [8]. In the very high energy γ-ray regime, PKS 0625-354 was discovered in 5.5 hrs of good quality data collected with H.E.S.S. in the late 2012 [7]. The observations with the array of four H.E.S.S. telescopes resulted in the detection with 6.1σ. No variability was found in these observations.

Along with the observations made with the H.E.S.S. telescopes, PKS 0625-354 was also observed by other observatories and instruments such as *Fermi*-LAT, *Swift*-XRT, *Swift*-UVOT, and ATOM. Significant variability was found in the X-rays and high-energy γ rays as seen with *Swift*-XRT and *Fermi*-LAT, respectively. The multifrequency observations of the source allowed for the modelling and interpretation of the broadband spectral energy distribution of the source and discussion of its interpretation. A one-zone lepto-hadronic and multi-zone leptonic models were presented and discussed. This comparison was concluded based on the energetics of the leptonic multi-zone model. Furthermore, the modelling supported the BL Lac nature of PKS 0625-354 over the radio-galaxy classification of this AGN. However, given the different properties of the source, the classification of PKS 0625-354 reminded unclear [7]. The properties are:

— The distance of this AGN ($z = 0.055$) makes it very distant for a non-beamed emitter. For comparison, the redshift of the two most distant radio galaxies is $z = 0.017$ (NGC 1275) and $z = 0.0217$ (3C 264), respectively. The distance of PKS 0625-354 would require a considerably high luminosity compared to the other radio galaxies.

— Authors of [9] suggested a blazar-like nature of the object based on spectroscopic optical observations of the AGN and a measurement of the intensity of [OIII] emission lines.

— The flux and the frequency of the synchrotron peak in the broadband spectral energy distribution are located between the UV and X-ray range. That also supports the BL Lac nature of the source. According to the blazar-envelope unification scheme [10], this synchrotron peak position is the most extreme one among all known VHE radio galaxies.

— The kpc-scale image of PKS 0625-354 shows two extended radio lobes as expected for FR I radio galaxy. However, the TANAMI reported the evidence for the one-sided pc-scale jet [11].

In view of the above arguments further coordinated observations of the sources seemed to be essential for understanding the nature of PKS 0625-354.

2. 2018 observations of PKS 0625-354

In November 2018, PKS 0625-354 was observed with five H.E.S.S. telescopes. The observational campaign started on November 1 and was continued for 10 consecutive nights. The total exposure of 17.5 h of good quality data resulted in significant detection with a signal of 8.7σ. The significant detection of the AGN was even possible while using only the first day of observations.

The night-by-night light curve of the source above an energy threshold of 200 GeV is presented in Fig. 1. A fit with a constant to the light curve points resulted in a χ^2 of 55 for 9 degrees of freedom, corresponding to

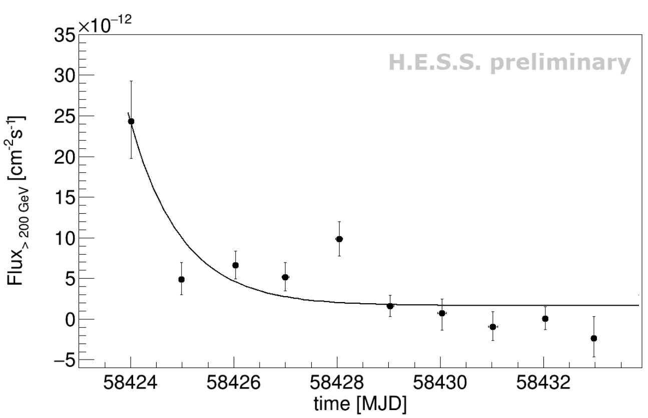

Fig. 1. Nightly integrated light curve above 200 GeV as seen with the H.E.S.S. telescopes in November 2018.

a probability of 1×10^{-8}. A description of the data with an exponential function defined as

$$F = F_0 + F_1\, 2^{-|t-t_1|/\tau}\,, \tag{1}$$

where F_0 is the baseline flux, F_1 the normalization flux at time t_1, and τ is the flux halving time-scale, allows one to calculate a halving time scale of $\tau = (17 \pm 7)$ hrs, with a χ^2 of 29.7 for 8 degrees of freedom, corresponding to a fit probability of 2×10^{-4}.

For the spectral analysis in the VHE band, three different periods were selected: *(i)* the entire set of data — 10 days of observations, *(ii)* the observations corresponding to the flaring state (including only the first night of observations), and *(iii)* the low state (including all data without a first night). For each dataset, the spectrum was described with a single power-law model defined as: $\mathrm{d}N/\mathrm{d}E = f_0 \left(\frac{E}{E_0}\right)^{-\Gamma}$, where f_0 is the normalization at the energy E_0 and Γ is the photon spectral index. The resulted spectral energy distributions are presented in Fig. 2.

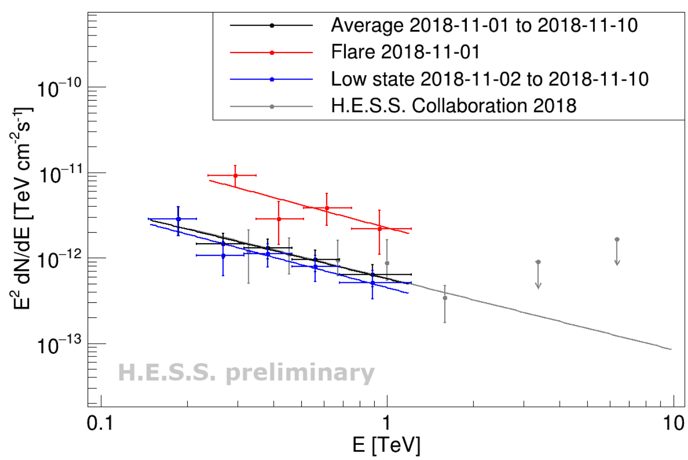

Fig. 2. Spectral energy distributions in different states of PKS 0625-354.

Parameters of these 3 spectral fits, listed in Table 2, clearly show flux variability, while the photon index remains constant. It is also worth mentioning that the low spectral state observed in November 2018 corresponds to the same spectral properties as reported by [7].

Together with the H.E.S.S. observations, PKS 0625-354 was monitored with *Swift* (3 day-by-day observations) and *Fermi*-LAT as a part of its regular observations. These instruments provided X-ray, optical, ultraviolet, and high-energy γ-ray observations, respectively. All periods of H.E.S.S. and multiwavelength observations are indicated in Fig. 3.

Table 2. Results of power-law fit of the spectra measured with H.E.S.S. The columns are: (1) state of the source; (2) the normalization at the energy E_0, in 10^{-12} TeV^{-1} cm^{-2} s^{-1}; (3) decorrelation energy in TeV; (4) photon index.

State	$f_0 \pm f_{\rm stat.} \pm f_{\rm syst.}$	E_0	$\Gamma \pm \Gamma_{\rm stat.} \pm \Gamma_{\rm syst.}$
Average state	$7.5 \pm 1.0 \pm 2.2$	0.4	$2.8 \pm 0.3 \pm 0.2$
Flaring state	$23.8 \pm 5.0 \pm 7.2$	0.4	$2.9 \pm 0.5 \pm 0.2$
Low state	$6.3 \pm 1.0 \pm 1.9$	0.4	$2.9 \pm 0.3 \pm 0.2$

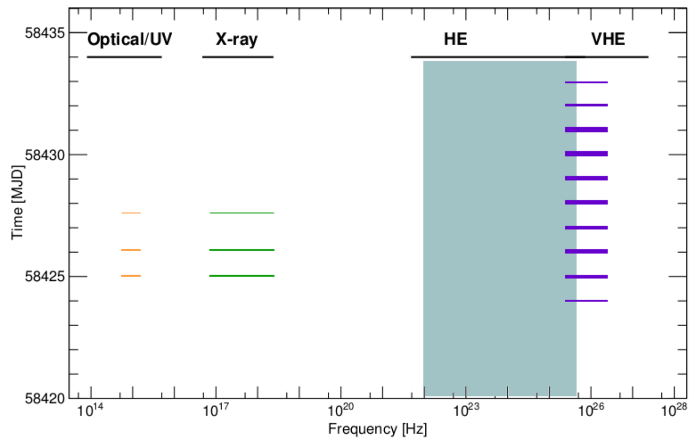

Fig. 3. Periods of H.E.S.S., *Fermi*-LAT, *Swift*-XRT, and *Swift*-UVOT observations of PKS 0625-354 being part of the 2018 campaign.

The multiwavelength dataset allows one to build the broadband spectral energy distribution of PKS 0625-354, which is presented in Fig. 4. The data simultaneous with the H.E.S.S. observations, *i.e.* observations which are called low-state data here, were fitted with a leptonic one-zone synchrotron-self-Compton model using the code of [12]. The results of the spectral fitting are presented in Fig. 4, while the model parameters are collected in Table 3. We note here that the presented modelling is only one out of several possibilities given the degeneracy in the model parameters. However, the presented solution works well for the set of multifrequency observations of PKS 0625-354. Such a one-zone synchrotron-self-Compton model was also used by [13], while this model did not work in [7] requiring a more sophisticated solution.

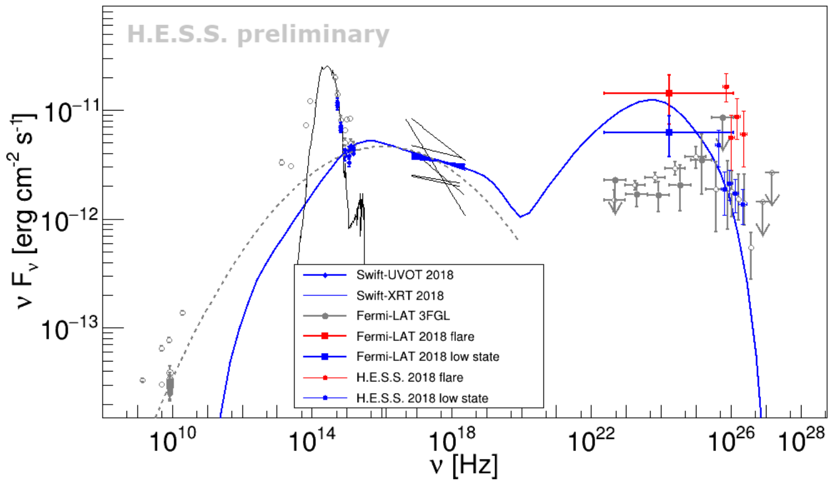

Fig. 4. (Colour on-line) Spectral energy distributions measured with the H.E.S.S. telescopes in 2018 and 2012. The red data points indicate the spectrum measured on November 1, while the data points and the line in blue show the spectrum and model, respectively, computed from the remaining data taken in November 2018. The grey points present archival observations of the source.

Table 3. Model parameters for the one-zone synchrotron-self-Compton modelling of the broadband spectral energy distribution. The columns are: (1) the bulk Lorentz factor; (2) the Doppler factor; (3) the viewing angle in degree; (4) and (5) the electron spectral indices below and above the break energy; (6) the minimal electron energy in $\log 10(E/\mathrm{eV})$; (7) the maximal electron energy in $\log 10(E/\mathrm{eV})$; (8) the break energy in $\log 10(E/\mathrm{eV})$; (9) the energy density of electrons in erg/cm^3; (10) the ratio of U_e to the magnetic field energy density U_B; (11) the magnetic field in G; (12) the radius of the emission region in cm.

Γ_j	δ	θ	p_1	p_2	E_min	E_max	E_br	U_e	η	B	R
5	6.7	8	2.0	3.2	8.0	11.7	9.6	0.6	6.7	1.25	1.7×10^{15}

3. Summary

PKS 0625-354 is a unique example of a non-blazar extragalactic TeV γ-ray emitter. Here, we reported on the first detection of significant variability in the very high energy γ rays of this AGN. The broadband spectral energy distribution of the source was described with good accuracy while using a single synchrotron-self-Compton model. A new set of simultaneous multiwavelength observations of the source describing the source, confirmed the mysterious nature of PKS 0625-354, the source that exhibits the features of two different subclasses of AGN: blazars and radio galaxies.

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REFERENCES

[1] S.P. Wakely, D. Horan, «TeVCat: An online catalog for Very High Energy Gamma-Ray Astronomy», *International Cosmic Ray Conference* **3**, 1341 (2008).

[2] J. Aleksić *et al.*, «Detection of very-high energy γ-ray emission from NGC 1275 by the MAGIC telescopes», *Astron. Astrophys.* **539**, L2 (2012).

[3] R. Mukherjee, «VERITAS discovery of VHE emission from the FRI radio galaxy 3C 264», *The Astronomer's Telegram* No. **11436** (2018). Available from: ATeL 11436.

[4] F. Aharonian *et al.*, «Is the giant radio galaxy M 87 a TeV gamma-ray emitter?», *Astron. Astrophys.* **403**, L1 (2003).

[5] F. Aharonian *et al.*, «Discovery of Very High Energy γ-ray Emission from Centaurus a with H.E.S.S.», *Astrophys. J. Lett.* **695**, L40 (2009).

[6] J. Aleksić *et al.*, «Detection of Very High Energy γ-ray Emission from the Perseus Cluster Head-tail Galaxy IC 310 by the MAGIC Telescopes», *Astrophys. J. Lett.* **723**, L207 (2010).

[7] H.E.S.S. Collaboration (H. Abdalla *et al.*), «H.E.S.S. discovery of very high energy γ-ray emission from PKS 0625-354», *Mon. Not. R. Astron. Soc.* **476**, 4187 (2018).

[8] D.H. Jones *et al.*, «The 6dF Galaxy Survey: final redshift release (DR3) and southern large-scale structures», *Mon. Not. R. Astron. Soc.* **399**, 683 (2009).

[9] K.A. Wills *et al.*, «Emission lines and optical continuum in low-luminosity radio galaxies», *Mon. Not. R. Astron. Soc.* **347**, 771 (2004).

[10] E.T. Meyer *et al.*, «From the Blazar Sequence to the Blazar Envelope: Revisiting the Relativistic Jet Dichotomy in Radio-loud Active Galactic Nuclei», *Astrophys. J.* **740**, 98 (2011).

[11] R. Angioni *et al.*, «Gamma-ray emission in radio galaxies under the VLBI scope», *Astron. Astrophys.* **627**, A148 (2019).

[12] R. Krawczynski *et al.*, «Multiwavelength Observations of Strong Flares from the TeV Blazar 1ES 1959+650», *Astrophys. J.* **601**, 151 (2004).

[13] Y. Fukazawa *et al.*, «Suzaku Observations of γ-ray Bright Radio Galaxies: Origin of the X-ray Emission and Broadband Modeling», *Astrophys. J.* **798**, 74 (2015).