

Discovery of VHE gamma-rays from the radio galaxy PKS 0625-354 with H.E.S.S.

Michał Dyrda^{*a}, Alicja Wierzcholska^{b,a†}, Olivier Hervet^c, Rafał Moderski^d, Mateusz Janiak^d, Michał Ostrowski^e and Łukasz Stawarz^e for the H.E.S.S. Collaboration

^a Institute of Nuclear Physics, PAS, ul. Radzikowskiego 152, 31-342 Kraków, Poland

^b Landessternwarte, Universität Heidelberg, Königstuhl 12, D 69117 Heidelberg, Germany

^c LUTH, Observatoire de Paris, CNRS, Université Paris Diderot, 5 Place Jules Janssen, 92190 Meudon, France

^d Nicolaus Copernicus Astronomical Center, ul. Bartycka 18, Warsaw, Poland

^e Astronomical Observatory of the Jagiellonian University, ul. Orła 171, 30-244 Kraków, Poland

E-mail: Michał.Dyrda@ifj.edu.pl

Most of the extragalactic objects detected so far in the very high energy (VHE) regime are blazars, but the discovered nearby radio galaxies: M87, Cen A and NGC 1275 of type FRI seem to constitute a new class of VHE emitters. The radio galaxy PKS 0625-354 was observed and detected ($\sim 6\sigma$) with the H.E.S.S. phase I telescopes in 2012, above an energy threshold of 250 GeV. The time-averaged VHE energy spectrum is well characterized by a power law model. The broadband light curve, including the available multiwavelength data, as well as the VHE data gathered with H.E.S.S. will be presented.

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*Speaker.

†Mobility Plus Fellow

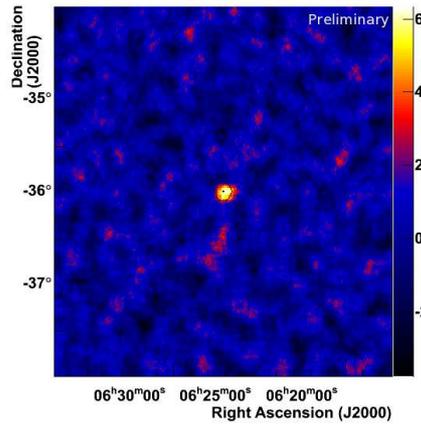


Figure 1: Significance map centred on the position of PKS 0625-354.

1. Introduction

Blazars are the most numerous class of extragalactic objects discovered in the very high energy (VHE; $E > 100$ GeV). These are active galactic nuclei with jets pointing close to the line of sight. However, there is a growing evidence that blazars are not the only extragalactic objects capable of VHE emission. With the detection of M 87, Cen A, IC 310 and Per A nearby radio galaxies of type FRI seem to constitute a new class of VHE sources [3, 5, 10].

Radio galaxies (RGs) are active galaxies with their relativistic jets oriented at intermediate to larger viewing angles with respect to the line of sight [18]. As a result of larger inclinations, the observed non-thermal emission produced within the innermost parts of the jets is not amplified by relativistic beaming and hence different emission components, typically not present in observed blazar spectra, may become prominent.

Increasing the number of VHE "γ-ray loud" RGs is important for several reasons. First, modelling of such sources provides an independent check of blazar models which are being developed, since RGs are considered as blazars observed at larger viewing angles [1, 7]. Second, γ-ray observations of RGs may reveal some "exotic" or at least non-standard processes possibly related to the production of high energy photons and particles within active nuclei and extended lobes [16, 17]. And third, increasing the sample of γ-ray RGs will enable us to understand the contribution of nearby non-blazar AGN to the extragalactic γ-ray background.

PKS 0625-354 (RA = $06^{\text{h}} 27^{\text{m}} 06.7^{\text{s}}$ DEC = $-35^{\text{d}} 29^{\text{m}} 15^{\text{s}}$, J2000) is a radiogalaxy of type FRI located in the Abell Cluster 3392, with a redshift value $z = 0.055$ [11]. It was detected by the *Fermi*-LAT in the high-energy (HE; $100 \text{ MeV} < E < 100 \text{ GeV}$) regime as a rather hard spectrum source $\Gamma_{\text{FGL}} = 1.88 \pm 0.06$ with a flux of $F_{1\text{GeV}-100\text{GeV}} = (1.43 \pm 0.11) \times 10^{-9} \text{ ph cm}^{-2} \text{ s}^{-1}$ [2].

2. H.E.S.S. data analysis and results

H.E.S.S. (High Energy Stereoscopic System) is an array of five imaging atmospheric Cherenkov telescopes (IACT) located in the Khomas Highland in Namibia, which observes the gamma-ray sky with energies from tens of GeV up to around 100 TeV [14].

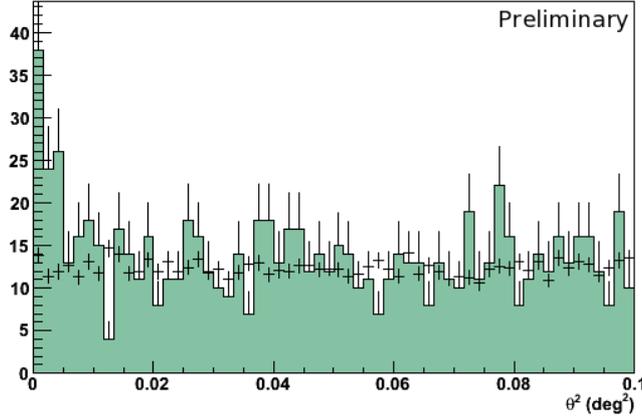


Figure 2: Distribution of θ^2 for on-source and normalized background. The excess is clearly visible in the region $\theta^2 < 0.01 \text{ deg}^2$, corresponding to a statistical significance 6.1σ .

PKS 0625-354 was observed in 2012 with H.E.S.S. phase I array of four IACTs [4]. All data collected during these observations were taken in *wobble mode* with an offset of 0.5° from the source. In this analysis, 5.5 hrs of good quality, life-time corrected exposure with at least 3 telescopes have been used. These data were proceeded using the Model analysis chain with standard cuts applied [13]. The total observed excess is 61 gamma-ray events, corresponding to a statistical significance of 6.1 standard deviations (σ). The significance map of PKS 0625-354 is shown in Figure 1. Figure 2 shows the on-source and normalized off-regions distributions as a function of squared angular distance from the source. The background is approximately flat and there is a point-like excess at small values of θ^2 , corresponding to the signal observed from PKS 0625-354.

The photon spectrum for the VHE data is shown in Figure 3. These data are well fitted ($\chi^2/\text{dof} = 24.2/21$) by a power-law function $dN/dE = N_0(E/E_0)^{-\Gamma}$, with photon index $\Gamma = 2.8 \pm 0.5$, normalization constant $N_0(E_0) = (2.77 \pm 0.70) 10^{-12} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ (statistical errors only) and decorrelation energy $E_0 = 0.58 \text{ TeV}$, and it is the energy for which the correlation between the normalization constant and photon index is equal zero and hence the uncertainties are minimized. An integral flux above the decorrelation energy $I (> 580 \text{ GeV}) = (8.7 \pm 3.2) \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$, which correspond to $\sim 4\%$ of the H.E.S.S. Crab Nebula flux [4], above the same threshold. As a cross-check, the observational data were analysed using independent analysis chain based on the event reconstruction algorithm - *ImPACT* [15].

3. Multiwavelength data analysis and results

3.1 High-energy observations with *Fermi*-LAT

The Large Area Telescope LAT on board *Fermi* satellite is a pair-conversion gamma-ray detector, which operates in the high-energy regime (HE; $100 \text{ MeV} < E < 100 \text{ GeV}$) [6]. *Fermi*-LAT analysis was performed using data from 54622 to 56778 MJD (68 months), what corresponds to period between the start of the mission and end of April 2014. For the analysis the photons with a zenith angle $< 105^\circ$ were selected. The binned maximum-likelihood method was

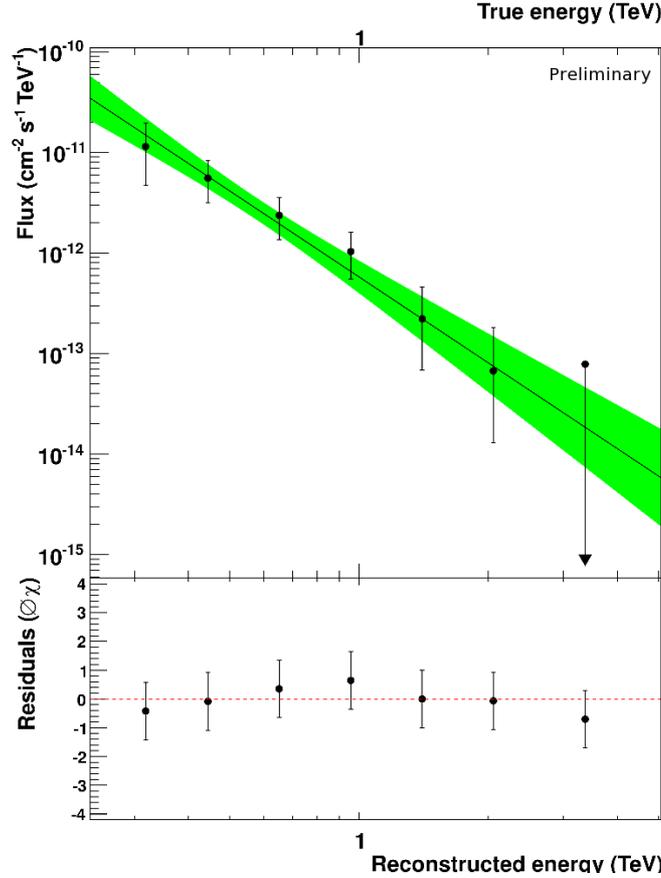


Figure 3: VHE spectrum of PKS 0625-354. The green region represents the 1- σ confidence bounds of the fitted spectrum for power-law hypothesis.

applied. The Galactic diffuse background was modelled using the `gll_iem_v05` map cube, and the extragalactic diffuse and residual instrument backgrounds were modelled jointly using the `isotropic_iem_v02` template. All the sources from the *Fermi*-LAT Third Source Catalog inside the region of interest of PKS 0625-354 were modelled. Two spectral models were tested with these data: power-law and a log-parabola. The likelihood test showed that the log-parabola model is preferred with the log-likelihood value of -253486 versus -253488 in case of power-law model and thus, the significance of the log-parabola with respect to the power-law hypothesis is $\sim 2 \sigma$. The fit parameters for a log-parabola model $dN/dE = N_0(E/E_b)^{-(\alpha+\beta \log E/E_b)}$ are: prefactor - $N_0 = (0.035 \pm 0.012) 10^{-9} \text{ cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1}$, index - $\alpha = 1.29 \pm 0.18$, curvature parameter - $\beta = 0.07 \pm 0.02$ and energy scale - $E_B = 100 \text{ MeV}$.

3.2 X-ray and UV observations with *Swift*

The *Swift* Gamma-Ray Burst Mission [8], launched in November 2004, is a multi-wavelength space observatory, equipped with three instruments: Burst Alert Telescope (BAT), X-ray Telescope (XRT) and Ultraviolet/Optical Telescope (UVOT). PKS 0625-354 was monitored with *Swift* in 4 observations with ObsIDs: 00039136001, 00049667002, 00039136002, 00049667001.

The data were analysed using HEASoft package v. 6.16 software¹ with CALDB v. 20140120. In the case of X-ray observations all the events were cleaned and calibrated using `xrtpipeline` task. Data in the energy range of 0.3-10 keV with grades 0-12 were analysed. For the spectral studies, data were grouped using `grappa` tool to have minimum 20 counts per bin and the spectra were fitted using XSPEC v. 12.8.2. Data were fitted with a single power-law model with Galactic hydrogen absorption value of $n_H = 6.5 \cdot 10^{20} \text{ cm}^{-2}$ [12] fixed as frozen parameter.

Simultaneously with XRT observations the source was monitored with UVOT. For each of ObsID, the instrumental magnitudes as well as the corresponding fluxes are calculated following `uvotsource` command, taking into account all photons from a circular region within radius of 5".

3.3 Optical monitoring with ATOM

Extragalactic H.E.S.S. targets are monitored with the 75 cm Automatic Telescope for Optical Monitoring (ATOM) located in Namibia at the H.E.S.S. site. The telescope is operational in Namibia since 2006 and monitored sources in UBVRI filters. The detailed description of the instrument can be found in [9]. PKS 0625-354 was monitored with ATOM in the R band during the period of November-December 2012 and in February 2013.

4. Conclusions

Observations carried with the H.E.S.S. phase I array in 2012 have established PKS 0625-354 as VHE gamma-ray source, which enlarges the extragalactic non-blazar source class. The available multiwavelength data as depicted in Figure 4, although not simultaneous, will be used in future in a more detailed SED study and offers the possibility to discriminate between different SED models. No significant variability of the VHE flux was noticed during the HESS observations period (see Fig. 4). In the HE range, analysis of observations simultaneous to H.E.S.S. ones yields only flux upper limit, although if the total *Fermi*-LAT data set is considered there is a hint of variability, as seen in Figure 4. A constant-flux yields the fit of the probability of $P(\chi^2/\text{dof} = 30.128/17) = 0.81$. The source is also variable in X-ray range (*Swift*/XRT) although there is no-simultaneous monitoring with VHE observations. In the optical band ATOM observations show almost constant flux in R band. Only 3-4 pointing observations in optical/UV energy bands do not allow either to claim or to exclude variability in these regimes.

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¹<http://heasarc.gsfc.nasa.gov/docs/software/lheasoft>

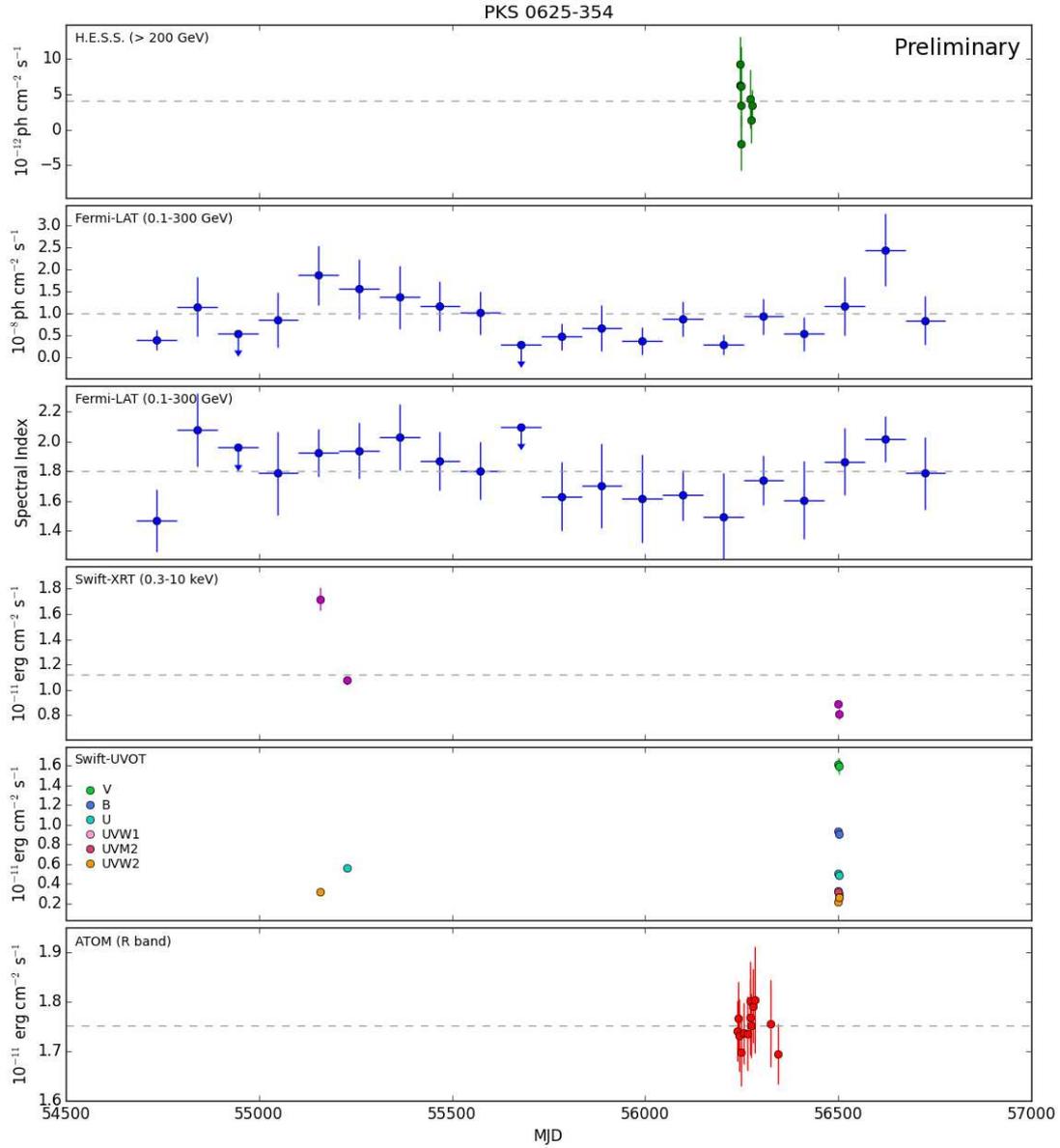


Figure 4: Light curves of PKS 0625-354 in different wavelengths. Top panel shows the H.E.S.S. lightcurve with nightly binning. The next two panels shows the HE flux changes and the *Fermi*-LAT inferred photon index changes. Another two panels are the X-ray and UV fluxes. Bottom panel are the ATOM observations in R-band.

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