The unprecedented VHE γ-ray outburst of PKS 1510-089 in May 2016

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PKS 1510-089 ($z = 0.361$), one of only a handful of flat spectrum radio quasars detected in the very high energy (VHE, $E > 100\,\mathrm{GeV}$) γ-rays, is known for its flux variability and complex multiwavelength behaviour. VHE observations by H.E.S.S. and MAGIC in May 2016 detected an unprecedented flare, both in intensity and in the shortness of its variability timescale. The flare lasted less than 48 hours, during which time the flux reached about 80 per cent of the Crab Nebula flux above 200 GeV. In addition, the intranight variability of this source was detected for the first time. Simultaneous observations in high energy (HE, $E > 100\,\mathrm{MeV}$) γ-rays performed with Fermi-LAT and optical R-band performed with ATOM show behaviour not consistent with simple simultaneous brightening in all bands. While a significant hardening of the spectrum is visible in HE, the flux increased only moderately. A simultaneous rise in daily-averaged optical flux was seen in the R-band. However, the intranight R-band flux evolution shows two prominent peaks, while only one is visible in the VHE range. These intriguing features of the flare will be presented in detail. We will also discuss possible explanations for the observed emission.

Keywords: gamma-rays; multiwavelength; blazars; PKS 1510-089.

1. Introduction

PSK 1510-089 is a flat spectrum radio quasar located at RA=$15^{\mathrm{h}}12^{\mathrm{m}}52.2^{\mathrm{s}}$, Dec=$-09^{\circ}06'21.6''$ (J2000), with the redshift of $z = 0.361$. It is a highly variable source of electromagnetic radiation in all energy bands, exhibiting a complex MWL behaviour.[1–4] It was first detected in the very high energy (VHE, $E > 100\,\mathrm{GeV}$) γ-ray band with High Energy Stereoscopic System (H.E.S.S., see Section 2.1) in 2009[5] Major Atmospheric Gamma-Ray Imaging Cherenkov (MAGIC, see Section 2.1) detected VHE γ-ray signal from PSK 1510-089 in 2012.[6] The first detection of variability in the VHE band occurred during an outburst in 2015.[7,8] The flux was variable on a daily time-scale. An exceptional VHE γ-ray outburst of PKS 1510-089 in May 2016 was observed both with H.E.S.S. and MAGIC, revealing intra-night variability for the first time, on which we report here. We also present results in the high energy (HE, $E > 100\,\mathrm{MeV}$) γ-rays and optical band.

2. Data analysis and results

2.1. *VHE γ-ray band*

H.E.S.S. is an Imaging Atmospheric Cherenkov Telescope (IACT) array located in the Khomas Highland in Namibia at an altitude of about 1800 m a.s.l. It consists of four 12-m telescopes (CT1-4) and a 28-m telescope (CT5) in the centre of the array. The energy threshold of the system under optimal conditions is ~ 50 GeV. However, because of technical problems in the observation period, only $\mathrm{CT}2-4$ data were used in the present analysis, resulting in higher energy threshold of ~ 200 GeV. H.E.S.S. observed PSK 1510-089 from MJD 57535 to 57545. A total of 31 runs (about 28 min per run) passed the standard quality selection[9] resulting in a total live time of 13.6 h. The data were analysed with the Model analysis chain using loose cuts.[10] The results were cross-checked and verified using the independent reconstruction and analysis chain ImPACT.[11]

The H.E.S.S. light curve for the entire observation period (MJD $57535-57545$) with nightly averaged flux above 200 GeV is shown with red points in panel (a) of Fig. 1. The signal was significantly detected only on the nights of MJD 57537/8 and 57538/9. The average flux above 200 GeV on the night of the highest flux (MJD 57538) was $(14.3\pm0.6)\times10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, corresponding to 56% of the flux from Crab Nebula above the same energy threshold (0.56 C.U.).[12] This was ~ 15 times higher than what H.E.S.S. measured in 2015.[8] We fitted the run-by-run based light curve with a constant. The hypothesis of constant flux was rejected at the level of $> 10\,\sigma$. On the night of the highest flux the source was observed for 4 runs, totalling in 1.8 h of data. The light curve with flux above 200 GeV is shown with red points in panel (a) of Fig. 2. Again the constant flux is ruled out on a run-by-run basis with $5.4\,\sigma$, confirming the first ever detection of VHE intra-night variability in PSK 1510-089. The flux above 200 GeV reached $(20\pm1)\times10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, equivalent to 0.8 C.U. The spectrum is best fitted with a power-law (PL) $F(E) = N_0 \times (E/E_0)^{-\Gamma}$ folded with exponential function representing γ-ray flux attenuation due to the extragalactic background light (EBL).[13] Spectral parameters are as follows: normalisation flux $N_0 = (19.0\pm0.8)\times10^{-10}\,\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,s^{-1}$, spectral index $\Gamma = 2.9\pm0.2$ and decorrelation energy $E_0 = 268$ GeV.[12] The intrinsic spectrum is shown in Fig. 3 with red points.

MAGIC is a stereoscopic system located in Canary Island of La Palma, at the height of 2200 m a.s.l.[14]. It consists of two identical 17-m IACTs. The standard trigger threshold of the MAGIC telescopes for low zenith angle observations is ~ 50 GeV.[15] However, from the MAGIC location, PSK 1510-089 is observable at zenith angles above 38°, resulting in higher trigger threshold of ~ 90 GeV for the present analysis. Nevertheless, we integrated flux above 200 GeV, in order to have both H.E.S.S. and MAGIC light curves in the same energy range. MAGIC observed PSK 1510-089 on MJD 57535/6 and for five consecutive nights between MJD 57538/9 and 57542/3. A total of 7.5 h of data were collected for the whole observation period, while 2.7 h of data were collected on the night of flare. For

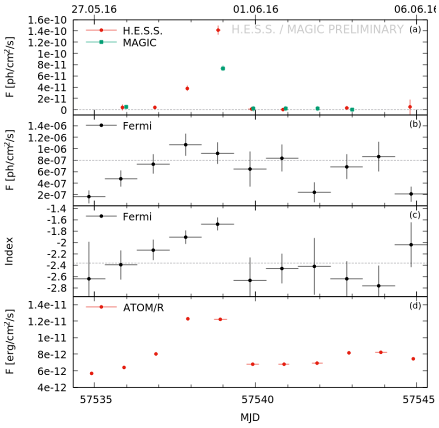

Fig. 1. PSK 1510-089 light curves for the MJD 57535 − 57545 period. **(a)** Nightly-averaged flux above 200 GeV measured with H.E.S.S. (red) and MAGIC (green). **(b)** Flux above 100 MeV averaged over 24 h and centred on VHE observations as measured by *Fermi*-LAT. **(c)** *Fermi*-LAT spectral index above 100 MeV obtained from integration over 24 h assuming PL spectral shape. **(d)** Nightly-averaged optical light curve in R-band from ATOM. Plot adopted from Ref. 12.

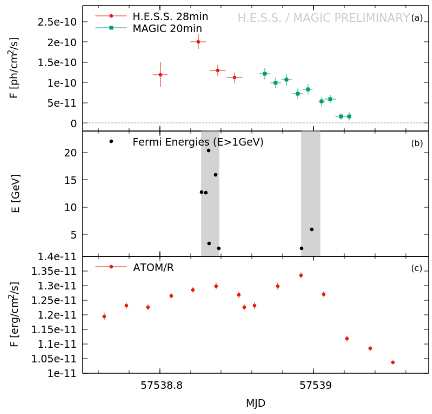

Fig. 2. PSK 1510-089 light curves for the night of the flare (MJD 57538/9). **(a)** Flux measured with H.E.S.S. (red) and MAGIC (green) above 200 GeV. **(b)** *Fermi*-LAT detected photons with $E > 1$ GeV. Grey bands represent LAT visibility windows of PSK 1510-089. **(c)** Optical light curve in R-band from ATOM. Each point represents an individual exposure of ~ 8 min. Plot adopted from Ref. 12.

a short period during the observation on MJD 57538/9, partial cloudiness caused variable rates in the MAGIC data acquisition. Those data were excluded based on pyrometer measurements,[16] leaving the final data sample of 2.53 h. The data were analysed using the the MAGIC analysis and reconstruction software (MARS).[15,17]

The MAGIC light curve for the entire observation period with nightly averaged flux above 200 GeV is shown with green points in panel (a) of Fig. 1. The signal was significantly detected only on the night of MJD 57538/9, when the average flux above 200 GeV was $(7.36 \pm 0.40) \times 10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$,[12] equivalent to 0.32 C.U. This was > 5 times higher than upper limits of the flux on the rest of the nights from this data set, ~ 4 times the flux MAGIC measured in 2015,[7] and as much as ~ 20 times the flux MAGIC measured in 2012.[6] Intra-night variability on MJD 57538/9 was also detected in MAGIC light curve, shown with green points in panel (a) of Fig. 2. Each point represents one 20-min run. A fit with a constant is ruled out with $> 10\,\sigma$. The flux changed from ~ 0.5 C.U. in the first to ~ 0.075 C.U. in the last run. The observed spectrum on the night of the flare was reconstructed between 60 and 700 GeV. Again it is best fitted with a PL folded with the EBL attenuation.[13] Spectral parameters are: $N_0 = (34.7 \pm 1.5) \times 10^{-10}\,\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,s^{-1}$, $\Gamma = 3.37 \pm 0.09$ and $E_0 = 175$ GeV.[12] The intrinsic spectral energy distribution (SED) is shown in

Fig. 3 with green points.
All uncertainties quoted are statistical only, for both observatories, while the systematic uncertainty on the energy scale is 15%.

We calculated variability time-scale from $t_{var} = \frac{1}{2}(F_i + F_{i+1})(t_{i+1} - t_i)/|F_{i+1} - F_i|$.[18] Smallest t_{var} is 18 ± 5 min between 7^{th} and 8^{th} MAGIC points (see Fig. 2). Based on causality argument we set upper limit on the size of the VHE γ-ray emission region $R \leq c\delta t_{var}/(1+z) = 1.2 \times 10^{15}(\delta/50)$ cm, where δ is relativistic Doppler factor. Adopting $\theta_j \sim 0.2/\Gamma$ for the jet opening angle,[19] where Γ is the relativistic Lorentz factor (here we use $\Gamma = \delta$), and assuming the γ-ray emission region fills the entire cross section of the jet, we estimated the distance of the emission region from the black hole (BH) to be $d \sim R/\theta_j \sim 3 \times 10^{17}(\delta/50)^2$ cm. It should be noted that both $\theta_j \sim 0.2/\Gamma$ and $\delta \sim 50$ are extreme values. Larger opening angle, or smaller Doppler factor would put the emission region closer to the BH. On the other hand, abandoning the assumption of filling the entire cross section of the jet, would allow the emission region to be located further down the jet.

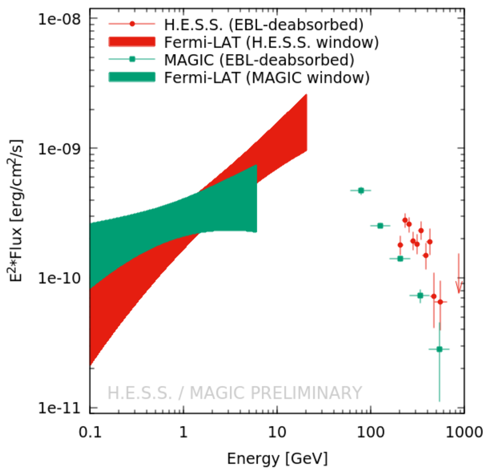

Fig. 3. PSK 1510-089 SED in HE and VHE band for the night of the flare. The H.E.S.S. data are given in red and the MAGIC ones in green points. The *Fermi*-LAT confidence regions are obtained by integrating over precise H.E.S.S. (red) and MAGIC (green) observation windows respectively. Plot adopted from Ref. 12.

2.2. *Multiwavelength picture*

We combined our data with observations in HE with *Fermi*-LAT and optical *R*-band observations with ATOM.

LAT is sensitive in the $0.02 - 300$ GeV interval.[20] In an all-sky-survey mode, it scans the entire sky in 3 hours, while any point in sky is observed continuously for 30 min. We analysed publicly available Pass 8 SOURCE class events with energy > 100 MeV in the region within $15°$ from the PSK 1510-089 position. We applied a zenith angle cut of $< 90°$. The analysis was performed with the ScienceTools software package version v10r0p5 using the P8R2_SOURCE_V6 instrument response function and the GLL_IEM_v06 and ISO_P8R2_SOURCE_V6_v06 models for the Galactic and isotropic diffuse emission,[21] respectively. We produced a light curve for the whole period of VHE observations, shown in panel (b) in Fig. 1, where each point represents flux integrated over 24 h, centred on VHE observation. For this purpose, we assumed a PL spectral model with parameters free to vary between bins. The flux variability is apparent, however smaller than in the VHE band. Indeed the change is slower and the flux level significantly lower than the historical maximum[2] in this band.

Inspecting the spectral index on 24-hour scale, a hardening of the HE spectra with the increase of the VHE flux can be seen, reaching 1.7 ± 0.1, and then dropping to average value of 2.368 ± 0.004 after the flare (see Fig. 1c). On the night of the flare, LAT detected 8 photons with $E > 1\,\mathrm{GeV}$ (Fig. 2b); 6 of them in the H.E.S.S. observation window (4 with energies in the $10 - 25\,\mathrm{GeV}$ interval), when the VHE flux was higher, compared to the MAGIC observation window when only two photons were detected, both with energies below 10 GeV. Combined HE – VHE SED is shown in Fig. 3. The LAT confidence regions were obtained by integrating over precise VHE observation windows and calculated up to the highest detected energies for the respective period. The spectral indices were $\Gamma = 1.4 \pm 0.2$ and $\Gamma = 1.7 \pm 0.2$ in the H.E.S.S. and MAGIC windows, respectively. We calculated the difference in the spectral indices between HE and VHE spectra ($\Delta\Gamma$) and logarithm of ratio between extrapolated HE and measured VHE fluxes ($\tau = \ln(F_{extra}/F_{obs})$) for both observation windows. We obtained $\Delta\Gamma = 1.5 \pm 0.3$ and $\Delta\Gamma = 1.7 \pm 0.2$, and $\tau = 3.9 \pm 1.4$ and $\tau = 5.4 \pm 0.9$ for H.E.S.S. and MAGIC windows, respectively. The SED peak was located in the $10 - 60\,\mathrm{GeV}$ interval. Possible causes of the spectral break are absorption of γ-rays in the broad line region (BLR), but also intrinsic effects such as Klein-Nishina regime, break in electron spectrum etc. Our calculations put the emission zone (see Section 2.1) just outside of the BLR if $R_{BLR} = 2.6 \times 10^{17}\,\mathrm{cm}$[6] is adopted.

ATOM is a 75 cm optical telescope located on the H.E.S.S. site,[22] monitoring H.E.S.S. γ-ray sources. The magnitudes of each flux point were derived with differential photometry using five comparison stars in the same field of view. The resulting fluxes were corrected for Galactic extinction. Nightly averaged light curve (Fig. 1d) shows a similar flux evolution as in VHE band. However, a comparison on a finer time-scale for the flare night (Fig. 2c) shows double-peaked structure, in contrast to the VHE light curve shape.

3. Summary

H.E.S.S. and MAGIC observed an exceptionally strong and fast flare from PSK 1510-089 in VHE, detecting for the first time intra-night variability in this band. Although we saw no obvious counterparts in lower energies, a significant hardening of the spectrum was detected in the HE. A HE–VHE spectral break could indicate a BLR absorption, however the shortest variability time-scale of 18 ± 5 min put the γ-ray emission region just outside of the BLR.

Acknowledgments

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MAGIC gratefully acknowledges financial support from the agencies and organisations listed at `https://magic.mpp.mpg.de/ack_201805/`.

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