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MAGIC and H.E.S.S. detect VHE gamma rays from the blazar OT 081 for the first time: a deep multiwavelength study

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OT 081 is a luminous blazar well known for its variability in many energy bands. The very-high-energy (VHE; $E > 100$ GeV) gamma-ray emission from the source was discovered by MAGIC and H.E.S.S. during flaring activity in July 2016, after a trigger from the Large Area Telescope (LAT) onboard the *Fermi* satellite. By analysing the multiwavelength light curves and the broadband spectral energy distribution (SED), we study the activity of the source and investigate four individual states of activity in the window from MJD 57575 to 57602. The intrinsic gamma-ray spectrum can be described by a power law with spectral indices of 3.27 ± 0.44 (MAGIC) and 3.39 ± 0.58 (H.E.S.S.) over energy ranges 60–300 GeV and 120–500 GeV, respectively. The combined contemporaneous high-energy (HE; $E > 100$ MeV) through VHE SED shows curvature and can be described by a log-parabola shape. A simple one-zone synchrotron self-Compton (SSC) model is not sufficient to describe the broadband SED. The presence of broad emission lines in the optical spectrum of the source challenges the categorisation of OT 081 as a BL Lac and, together with the emission scenarios tested, points to the possibility that the source is transitional in nature between a BL Lac and a flat-spectrum radio quasar.

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1. OT 081

OT 081 is a luminous blazar located at redshift $z = 0.32$ [1] and also known as PKS 1749+096 and 4C 09.57. In these sources, the emission from the jet pointing toward the observer is enhanced because of the Doppler beaming effect. The relativistic beaming also enhances violent variability, which is commonly observed in blazars [2]. OT 081 has indeed shown strong variability in the optical [3], X-ray [4], and remarkably in the radio band as documented by UMRAO observations [5][1] and others [5, 35, 36]. The jet of OT 081 is characterised by a one-sided curved morphology at all epochs and all frequencies [6], and superluminal motion of jet features has been reported with apparent speeds in the range of ∼ 1–14c [5, 7–9]. Optical polarization has been detected up to 32% [10, 34]. Initially classified as a HBL (high-frequency peaked BL Lac) by [11, 12] because of its radio spectrum peaked above 10 GHz, a few years later it was suggested that OT 081 is a flat-spectrum radio quasar (FSRQ), presenting an inverted radio spectrum during flares [13, 14]. In fact, from these studies, the continuum radio spectrum is observed to be clearly inverted in the maxima, with the turnover at 22–100 GHz.

In the common categorisation of blazars, FSRQs (unlike BL Lac objects) present strong and broad emission lines in their optical spectrum, owing to the presence of gas outside of the jet cone. The redshift of OT 081 has been determined by [1] with an optical spectrum obtained during a faint state ($V \approx 19$ mag) of the source. The spectrum clearly reveals emission lines attributed to Hβ and the [O III] $\lambda\lambda$4959, 5007 doublet with equivalent width (EW) ≈ 10 Å, and marginally the emission line of [O II] λ3727. A more recent spectrum taken on 30 August 2016 is available in the Steward Observatory database[2], confirming the detection of the emission lines with $EW_{H\beta} = 3$ Å and $EW_{[O\ III]\ \lambda5007} = 5$ Å. The Hβ line luminosity is $\sim 5 \times 10^{41}$ erg s^{-1}. The existence of a broad-line region (BLR) is consistent with the presence of strong emission lines in the optical spectrum, suggesting that the source is intermediate between a BL Lac object and a FSRQ. This conclusion was anticipated by [15], who proposed a classification of blazars based on the luminosity of the broad emission lines measured in Eddington units. [16] suggest that some BL Lacs could be a subclass of blazars with a close pair of binary black holes (BBHs) which has decreased the amount of gas present in both the narrow-line region and the BLR. In this model, BL Lacs are at a very late stage of galaxy-galaxy merging, and they may have an optically thin BLR owing to the lack of gas.

Emission from OT 081 in the high-energy gamma-ray range (HE; $E > 100$ MeV) has been reported by [17]. The source is present in the Third Catalog of Hard *Fermi*-LAT Sources [3FHL, 18], and recently in the Fourth Source Catalog [4FGL, 19] as 4FGL J1751.5+0938, with a spectral index of 2.55 ± 0.01. The presence of very-high-energy (VHE; $E > 100$ GeV) gamma-ray emission, detected during a flaring state of OT 081 in July 2016 and reported here, allows a deep characterisation of the multiwavelength (MWL) spectral energy distribution (SED).

[1] https://dept.astro.lsa.umich.edu/obs/radiotel/gif/1749_096.gif
[2] http://james.as.arizona.edu/~psmith/Fermi/DATA/Objects/pks1749.html

2. Observations

Emission in the VHE gamma-ray band was detected for the first time by MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov telescopes) and by H.E.S.S. (High Energy Stereoscopic System) in July 2016 [20, 21]. MAGIC started to observe OT 081 on MJD 57591 (22 July 2016), triggered by the high optical state and by high-energy photons detected by *Fermi*-LAT [22, 23]. The detection happened on MJD 57593 (24 July 2016), with a significance of 9.7σ in 1.64 hr of observation. A total of 2.03 hr of data (corresponding to three nights of observations) were collected in the zenith angle range from 15° to 30° and the analysis was performed using the standard MAGIC analysis framework MARS [24, 25].

Following the *Fermi*-LAT trigger on a flaring state of OT 081 [26] and the subsequent X-ray and UV observations that showed correlated gamma-ray/X-ray/UV/optical activity of the source, H.E.S.S commenced observations on MJD 57591 (22 July 2016). They continued for 6 consecutive nights, until MJD 57596 (27 July 2016). 26 observation runs of 28 min each were obtained in the zenith angle range from 33° to 47°, with a mean zenith angle of 38°. All data passed the standard data-quality selection criteria [27], translating to a total of 11.7 hr of observations (10.1 hr after acceptance correction owing to the wobble offsets around the nominal source position) available for analysis.

The pair-conversion Large Area Telescope (LAT) onboard the *Fermi* satellite monitors the gamma-ray sky in survey mode every 3 hr in the energy range from 20 MeV to > 300 GeV [28]. For this work, a region of interest (ROI) centred around OT 081 [4FGL J1751.5+0938, 19] with a radius of 10° was used. The data sample was selected around the flare detected by the LAT and the Cherenkov telescopes MAGIC and H.E.S.S., from 6 to 31 July 2016 (MJD 57575–57600). The data reduction of the events of the Pass8 `source` class (P8R3) was performed with the Fermitools software package (v. 2.0.0) in the energy range 0.1–100 GeV.

Many other instruments and observatories were involved in the study of this flaring activity, making it possible to perform a deep MWL study: the XRT instrument onboard the *Neil Gehrels Swift Observatory (Swift)* [*XRT*, 29], ATOM (Automated Telescope for Optical Monitoring), The Tuorla blazar monitoring program[3], the 0.76 m Katzman Automatic Imaging Telescope [KAIT; 30] at Lick Observatory, the 0.7 m AZT-8 telescope of the Crimean Astrophysical Observatory[4], the 0.4 m telescope LX-200 in St. Petersburg, the 2 m Liverpool Telescope [LT; 31] located on the Canary Island of La Palma, the 1.83 m Perkins Telescope at Lowell Observatory (Flagstaff, AZ), the Atacama Large Millimeter/submillimeter Array (ALMA)[5], and the Very Long Baseline Array (VLBA) at 43 GHz obtained within the VLBA-BU-Blazar program[6]. VLBI data in particular revealed the ejection of a superluminal knot and its subsequent passage through a stationary feature as a possible cause of the HE gamma-ray activity. The detailed VLBI analysis will be shown in a companion paper in preparation [32].

[3] http://users.utu.fi/kani/1m/
[4] http://craocrimea.ru/ru
[5] https://www.eso.org/public/teles-instr/alma/
[6] www.bu.edu/blazars/VLBAproject.html

3. MWL light curves

Figure 1 presents the preliminary MWL light curves in order of decreasing energy starting from the top panel. The four vertical dashed lines (P1, P2, P3, and P4) indicate four different snapshots of the light curves. P1, centred on MJD 57585.5 (17 July 2016), describes an enhanced state in *Fermi*-LAT, with a flux of $(3.9 \pm 0.35) \times 10^{-6}$ ph cm^{-2} s^{-1}. P2 marks enhanced activity from *Fermi*-LAT and *Swift*-XRT on the same night MJD 57589 (20 July 2016). The state during which the richest simultaneous dataset was obtained is marked by P3, on MJD 57593 (24 July 2016). Finally, P4 (MJD 57595; 26 July 2016) is considered to be a baseline for our study, since it represents a state of low VHE gamma-ray activity.

In the top panel of Fig. 1 the VHE gamma-ray light curves from MAGIC and H.E.S.S. are shown. The HE gamma-ray activity decreased during the detection of VHE gamma rays. In [33], where this flaring activity is studied with a focus on the gamma-ray data from *Fermi*-LAT in the energy range 0.1–300 GeV, a flux of 2.9×10^{-6} ph cm^{-2} s^{-1} for MJD 57588 using a 3-day binning is reported. Here for the *Fermi*-LAT light curve a single-day binning is used, and a distinction between the two peaks (P1 and P2 vertical dashed lines) is made. The flux obtained for *Fermi*-LAT in the energy range 0.1–300 GeV is $(3.92 \pm 0.35) \times 10^{-6}$ ph cm^{-2} s^{-1} and $(4.21 \pm 0.23) \times 10^{-6}$ ph cm^{-2} s^{-1}, respectively.

The highest value of the X-ray flux is observed on MJD 57589.6 (20 July 2016), four nights before the VHE gamma-ray detection. Among the 9 nights observed in the X-ray band, the constant-flux hypothesis is rejected with $> 10\sigma$ confidence level. The PWL (power-law) model can describe the observed spectra in all of the cases. The X-ray flux ($F_{2-10\,\mathrm{keV}}$) on the night MJD 57589.6 (20 July 2016) was $(1.56 \pm 0.09) \times 10^{-6}$ erg cm^{-2} s^{-1}, the photon index $\Gamma_X = 1.33 \pm 0.06$, and the χ^2/d.o.f. = 1.27/26.

On MJD 57593.7 (24 July 2016), a higher flux density is observed; the highest value is for the *V* band, reaching 3.94 mJy. In the optical band, data from many instruments were collected, and the major activity described by the presented light curves is reached during the VHE gamma-ray flaring state centred on P3. The activity then decreases to the usual low state, typically around 1 mJy[7]. As is typical of this source [35, 36], the light curve at higher radio frequencies (ALMA curve; mm-radio band) shows more variability with respect to the lower radio frequencies (OVRO; 15 GHz), for which the light curve is quite flat. Considering a wider time window, the light curves at 250 GHz and 320 GHz appear to be in an enhanced state for a duration of ~ 3 months starting from ~ MJD 57540.

4. Conclusions

The discovery of OT 081 at VHE gamma rays allowed us to study its broadband emission during a period of time that spans from MJD 57575 to MJD 57602 (6 July to 02 August 2016). Four interesting states of the source were identified for detailed study. For the first time this source has been observed to emit VHE gamma rays, and data collected by the MAGIC and H.E.S.S. telescopes

[7] https://users.utu.fi/kani/1m/HB89_1749+096_jy.html

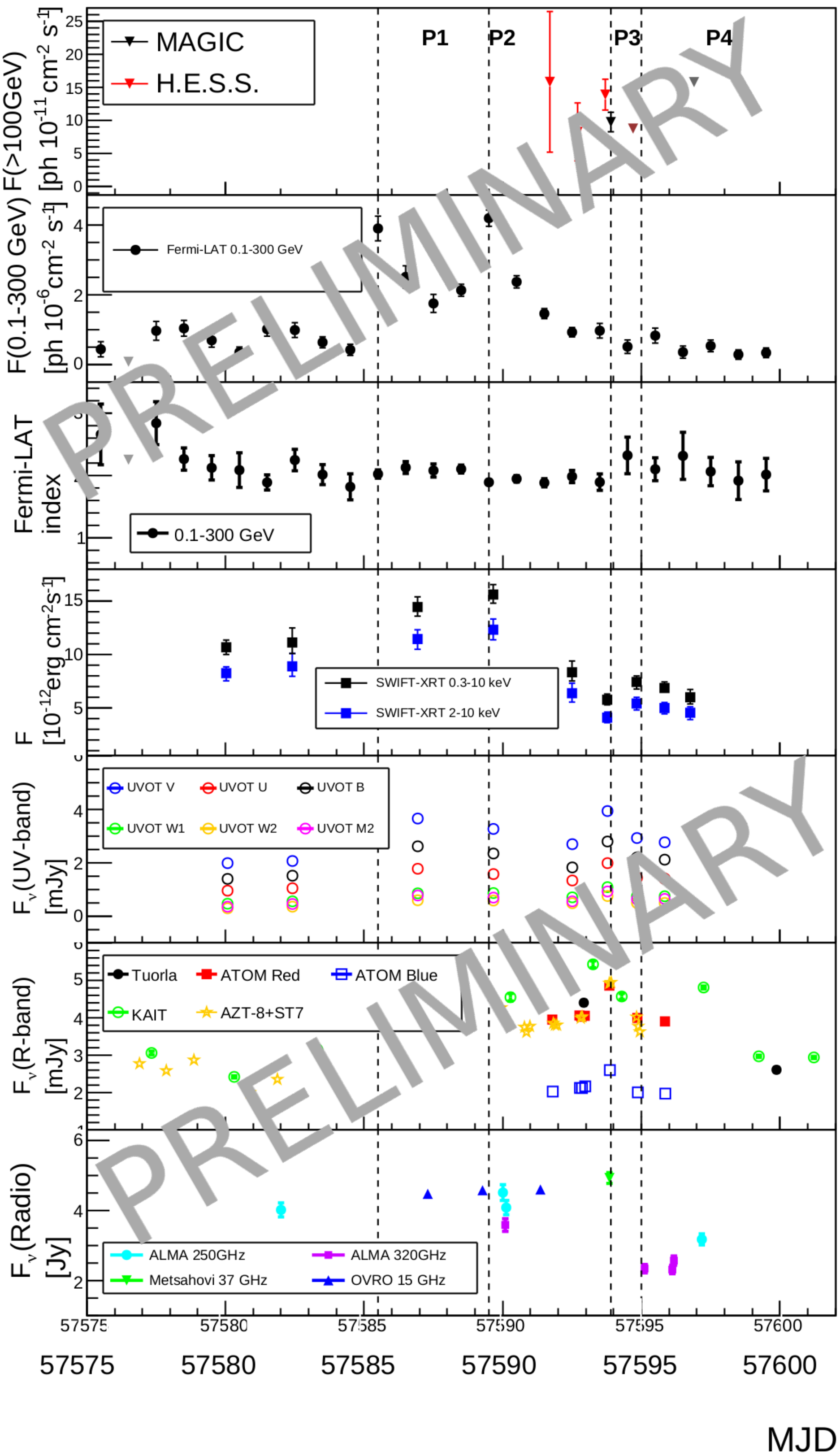

Figure 1: Preliminary MWL flux and index curves of OT 081 during the period from MJD 57575 to MJD 57602 (6 July to 02 August 2016). Vertical dashed lines P1 (MJD 57585.5; 17 July 2016), P2 (MJD 57589.5; 20 July 2016), P3 (MJD 57593; 24 July 2016), and P4 (MJD 57595; 26 July 2016) indicate the four states of the source that were identified.

have been used to study the flaring activity together with many other MWL instruments. The HE gamma-ray spectrum for P3 was found to have a Γ photon index of 1.98 ± 0.16, while the VHE gamma-ray spectrum was softer with a Γ index of 3.27 ± 0.44 for MAGIC and 3.39 ± 0.58 for H.E.S.S. Details on the modeling of the states of activity (P1, P2, P3, and P4) and the respective emission scenarios will be disclosed by [32].

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