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Studying the long-term spectral and temporal evolution of 1ES1959+650

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The high-frequency peaked BL Lac type object (HBL) 1ES 1959+650 is one of the brightest blazars in the very-high-energy (VHE, $E \gtrsim 100$ GeV) gamma-ray sky. HBLs have been proposed as possible neutrino emitters implying the presence of hadrons in the emission mechanisms. In 2002, AMANDA reported neutrino candidates from this source simultaneously observed with a gamma-ray flaring activity without an X-ray emission enhancement, interpreted as an orphan flare. Standard one-zone synchrotron self-Compton (SSC) emission models cannot explain this behavior. The MAGIC telescopes have been observing 1ES 1959+650 since 2004. An extreme outburst triggered by multiwavelength observations reaching 300% of the Crab nebula flux level above 300 GeV was detected in 2016. Leptonic and hadronic models are equally successful in describing the observed emission. To study the long-term behavior and the characteristics in different emission states of 1ES 1959+650, we have densely monitored it since 2017 for more than 300 hours. Together with the FACT monitoring (more than 2000 hours since 2012), this is the most intense monitoring for any blazar after Mrk 421 and Mrk 501 in the VHE range. The monitoring shows a decline of the VHE flux with occasional flaring episodes reaching in 2019 a low-state emission corresponding to 10% of the Crab nebula.

We present the long-term monitoring study results using multiwavelength data from MAGIC, FACT, *Fermi*-LAT, *Swift*, OVRO and Tuorla. Lastly, we discuss the differences in the broadband spectral energy distributions between the flaring states from 2016 and the low state in 2019.

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1. Introduction

Active galactic nuclei (AGN) are the innermost parts of galaxies whose brightness outshines the rest of the host galaxies. Some AGN have jetted emission from relativistic particles. AGN whose jetted emission is aligned to our line of sight are known as blazars. The boosted emission of these objects may be detectable in the very-high-energy (VHE, $E \gtrsim 100$ GeV) gamma-ray band with the current generation of instruments.

Blazars show a highly variable non-thermal continuum emission whose spectral energy distribution (SED) spans over a very wide range of energies from radio up to VHE gamma rays. Although it has been studied for several decades, the particle acceleration mechanisms and the origin of the variability of the broadband emission are still uncertain. The broadband SED exhibits a two-hump structure, which can be explained by several emission models. Relativistic charged particles in magnetic fields emit synchrotron radiation, which is observed as the lower energy hump. The origin of the higher energy hump is still controversial. Inverse Compton scattering of the synchrotron photons by the same population of relativistic electrons (synchrotron self Compton, SSC) successfully reproduces some observed spectra. Another possibility is that the low-energy photons up-scattered to yield gamma rays are instead external to the jet (external Compton, EC). The simplest framework that is usually capable of explaining the broadband SED emission satisfactorily is the one-zone model (see e.g. [1]). More complex scenarios with multiple emission zones are sometimes required to interpret the observations. Alternatively, scenarios in which hadrons are accelerated are proposed as well to explain the broadband emission from these objects (e.g. [2]). In this case, neutrinos would also be emitted. Some blazars show very dim or even no features in their optical/ultraviolet spectra. They are dubbed BL Lac objects (BL Lacs hereafter). Depending on the energies of the synchrotron hump, BL Lacs can be further categorized as low-frequency-peaked (LBL), intermediate-frequency-peaked (IBL), and high-frequency-peaked (HBL) BL Lac objects.

1ES 1959+650 is one of the nearest and brightest HBL ($z = 0.048$, [3]) in the VHE gamma-ray band. It is among the first TeV blazars detected roughly 20 years ago [4] and therefore it is one of the most studied BL Lacs. HBL, 1ES 1959+650 among them, are considered as possible neutrino emitters. A neutrino candidate detection was reported in 2002 by AMANDA [5] coincidentally with a gamma-ray flare in the absence of X-rays contemporaneous enhancement activity, which pointed towards hadronic acceleration scenarios.

The source underwent a period of extreme activity in 2016 reaching more than 3 Crab units (CU) [6] – its highest flux level since the major outburst in 2002 [7]. During the 2016 flare, intra-night variability at sub-hour scales was found. Searches for neutrino candidates coincidental with the location of 1ES 1959+650 during this major flare were conducted without success [8].

In this work, we describe the long-term multiwavelength monitoring observations of this source in the last few years. Subsequently, we present the preliminary results yielded comparing its different flux-states to those reported on the unusual 2016 VHE flare.

2. Multiwavelength observations

1ES 1959+650 was monitored by several instruments along the entire electromagnetic spectra. In what follows, the different multiwavelength observations included in this work are described.

MAGIC: The Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) telescopes comprise two 17-m diameter imaging atmospheric Cherenkov telescopes (IACT) observing the sky in VHE gamma rays. They are situated at Roque de los Muchachos Observatory in the Canary island of La Palma (Spain) at an altitude of 2200 m above sea level. MAGIC telescopes operate in the range of energies from about 50 GeV up to several tens of TeV. Its sensitivity for energies above 300 GeV is about 0.7% of the Crab nebula flux for 50 hours of mid-zenith angle observations assuming point-like sources with Crab-like spectra (see Table A.6 of [9]). To enlarge its duty cycle, MAGIC also observes under moonlight conditions as described in [10] with the drawback of increasing its energy threshold. MAGIC has been densely observing 1ES 1959+650 since 2016 for more than 300 hours, although there are previous sparser observations. MAGIC data included in this work are from 2015 to 2019. We only consider observations carried out with low night sky background (NSB) and in the range of zenith angles 35-50 degrees which allow for safely establishing an energy threshold of 300 GeV for the MAGIC light curve. The analysis of the data was done using the MAGIC Analysis and Reconstruction Software [11].

FACT: The First G-APD Cherenkov Telescope (FACT, [12]) is an IACT with a mirror area of 9.51 m^2 located beside the MAGIC telescopes. FACT is sensitive to gamma rays in the energy range from several hundreds of GeV to several TeV. Due to its detection principle based on silicon photo-multipliers sensors, it can operate with a large duty cycle. 1ES 1959+650 has been densely monitored by FACT. From 2015 to 2019, 1830 hours of physics data have been collected. The energy threshold for the light curve is about 700 GeV. The temporal binning chosen was mixed, i.e. nightly for 2016 and wider bins for the rest of the observations during the low state of the source. Data were analyzed using the Modular Analysis and Reconstruction Software [13].

***Fermi*-LAT:** The Large Area Telescope (LAT, [14]) is one of the instruments installed on the *Fermi* Gamma-ray Space Telescope, launched on 11 June 2008. The energy range covered by LAT is between 20 MeV and 300 GeV. LAT is monitoring the whole sky every three hours, which enables us to monitor any celestial source continuously. We performed the binned likelihood analysis of the data from 24 November 2016 (MJD: 57716) to 6 December 2019 (MJD: 58823) in the energy range 0.3-300 GeV using 3-day and 7-day temporal binning.

***Swift*-XRT** and ***Swift*-UVOT:** The Neil Gehrels *Swift* Observatory was designed for Gamma-Ray Burst observations and has been operating since 2004. The X-Ray Telescope (XRT, [15]) observes in the energy range 0.2-10 keV. The Ultraviolet Optical Telescope (UVOT, [16]) enables to perform simultaneous observation with XRT using ultraviolet and optical band filters (UVW1, UVM2, UVW2, and U, B, V, respectively) covering the wavelength range 170-650 nm. Both instruments onboard the Neil Gehrels *Swift* satellite have regularly observed 1ES 1959+650 resulting in a good observations coverage for the period studied here.

OVRO: We collected radio data at 15 GHz from the Owens Valley Radio Observatory (OVRO) 40-m telescope. The observations and data reduction were done following the procedure described in [17].

Tuorla: 1ES 1959+650 was regularly observed in the optical R-band as part of the Tuorla blazar monitoring program[1] with the 60-cm telescope Kungliga Vetenskapsakademien (KVA) located also on La Palma. Data were analyzed following the procedure described in [18].

[1] http://users.utu.fi/kani/1m/

3. Results

The long-term MAGIC light curve for energies larger than 300 GeV from the monitoring of the source is presented in Figure 1. The period covered in this work ranges from 2015 to 2019. We identified several flux states of the source. Apart from the exceptional outburst that occurred in 2016 [6], there were three flaring episodes in 2015, 2017 and 2018 in which 1ES 1959+650 reached $\sim$ 1 CU. On the other hand, the observations from 2019 revealed a steadily quiescent-flux state at the level of $\sim$ 0.2 CU. The flux values from the 2016 observations, grey data points in Figure 1, were already published in [6].

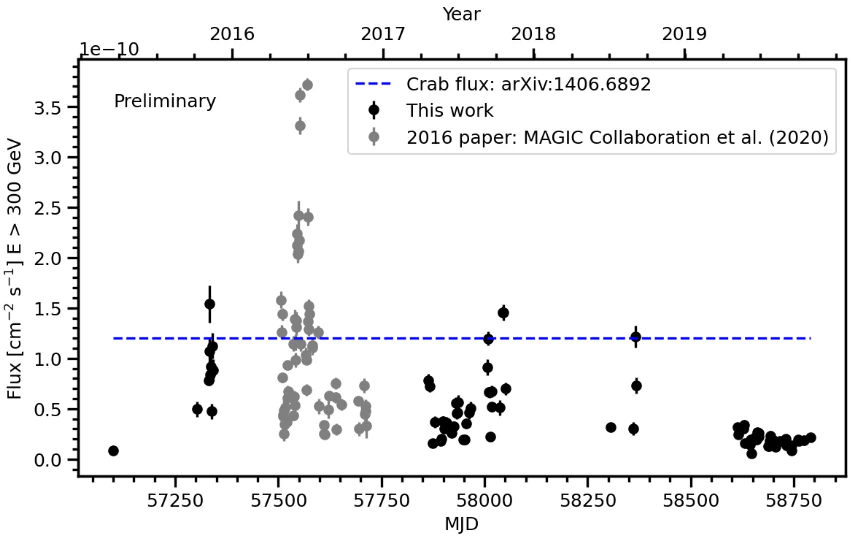

Figure 1: Preliminary MAGIC light curve (1-day binning) for energies above 300 GeV from 2015 to 2019. The data points correspond to observations under low NSB. For reference, the Crab nebula flux from [19] is depicted by the blue dashed line. 2016 data points (grey) were taken from [6].

Moreover, the light curves from the multiwavelength observations detailed in section 2 are presented in Figure 2. We first note that the extreme gamma-ray flare in 2016 was not followed in others energy bands whereas in 2017 there was a flare in all the wavebands. Finally, during the VHE low-flux state in 2019, an enhancement of the activity in the optical to radio bands was seen. To compare the large flaring state from 2016 with the quiescent period in VHE gamma rays from 2019, we selected a period representative of this low-flux state for which there were contemporaneous MAGIC and *Swift* observations, namely August 2019. The integral flux from this data sample is presented in Table 1 and compared to the exceptional flux from the 2016 flare when the source reached more than 3 CU. We also characterized the VHE gamma-ray SED from this period. The fitting parameters assuming a power-law function are presented in Table 1. The corresponding values from the 2016 flare are also shown for comparison. VHE spectra from MAGIC observations were de-absorbed using the extragalactic background light model described in [20].

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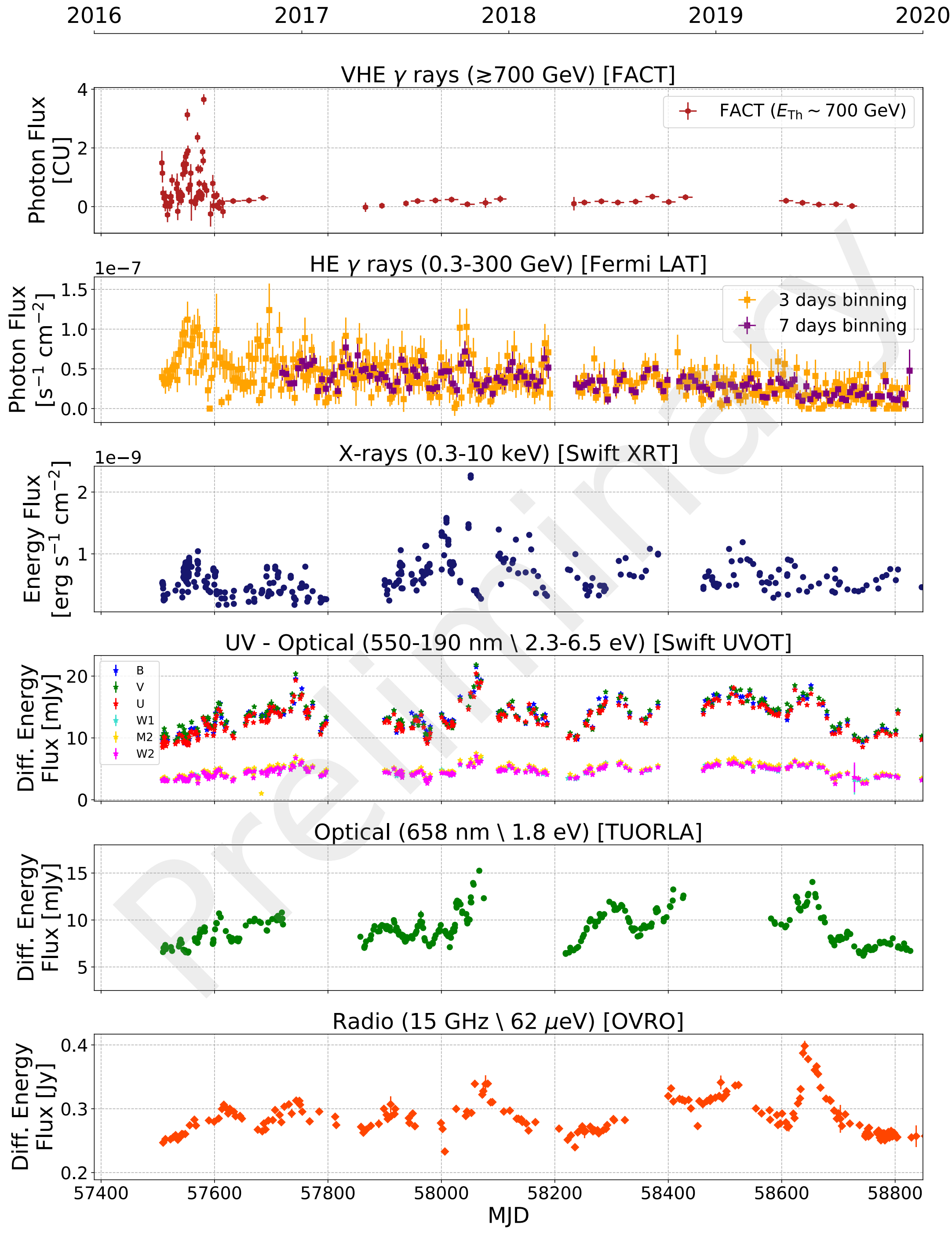

Figure 2: Multiwavelength light curves from all the instruments indicated in section 2. From top to bottom: VHE gamma rays from FACT ($E_{\rm Th} \sim 700$ GeV). HE gamma rays with energies in the range 0.3-300 GeV from *Fermi*-LAT. X-rays in the energy range 0.3-10 keV from *Swift*-XRT. Optical and UV observations in different bands by *Swift*-UVOT. Optical data in R band centered at 658 nm from Tuorla observatory. In the bottom panel, radio observations at 15 GHz from OVRO.

Table 1: MAGIC integral flux above 300 GeV and fit spectral parameters from August 2019 SED (values are preliminary). For comparison, integral flux and spectral parameters from 13 June 2016 [6] are also included.

Date	Flux (E > 300 GeV) [CU]	f_0 [TeV^{-1} cm^{-2} s^{-1}]	E_0 [GeV]	Spectral index
2016-06-13	3.4 ± 0.1	$(1.81 \pm 0.05) \times 10^{-9}$	300	-2.00 ± 0.02
August 2019	0.12 ± 0.01	$(4.9 \pm 0.3) \times 10^{-11}$	400	-2.5 ± 0.1

The SED corresponding to each of these different flux states in the VHE gamma-ray band from Table 1 are shown in Figure 3. A one-zone SSC model can describe satisfactorily the observed SEDs from both periods.

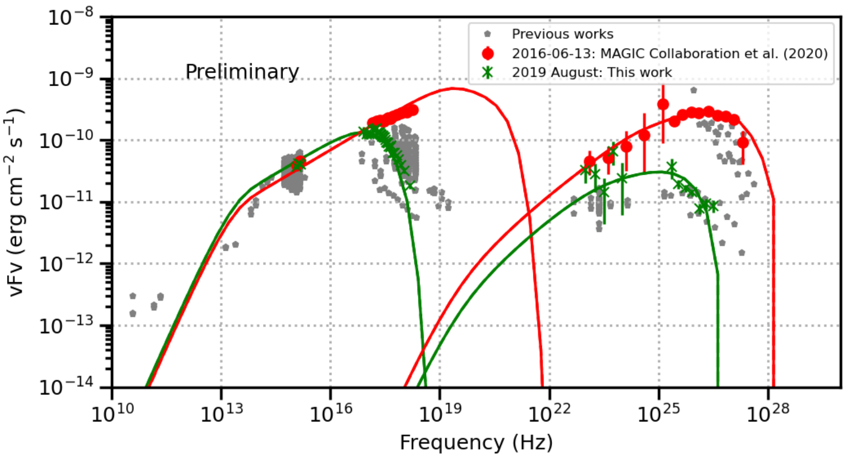

Figure 3: Multiwavelength SEDs from MAGIC, *Fermi*-LAT, *Swift*-XRT and *Swift*-UVOT. The August 2019 SED is indicated by green crosses and the published SED from 13 June 2016 [6] is represented by red circles. Both SEDs are modeled assuming a one-zone SSC scenario. Archival observations (grey pentagons) were compiled from SSDS SED builder (https://tools.ssdc.asi.it/) and references therein.

4. Summary

The preliminary results of the long-term multiwavelength monitoring of 1ES 1959+650 from 2015 up to 2019 have been presented. In this period, several flux states of the source were observed. Aside from the extremely high-flux level spotted in 2016, the source has gone through various VHE high-flux states in 2015, 2017 and 2018 reaching Crab-like flux levels. Interestingly, 2017 flares were accompanied by corresponding high states in X-ray, optical/UV and radio bands. On the other hand, 1ES 1959+650 was found to be in a steady and low-flux state with fluxes ~ 0.2 CU during 2019. We extracted the broadband spectral energy distribution from certain periods characteristic of each flux state and modeled them assuming a one-zone SSC scenario. A detailed study of this source will be presented in a dedicated upcoming publication by the MAGIC Collaboration.

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