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The broadband 3-year monitoring of the blazar 1ES 1959+650: a SED analysis of the low state

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The Spectral Energy Distribution (SED) of blazars consists of two components. The low-energy bump is interpreted as synchrotron radiation from accelerated electrons, while the high-energy one is produced via inverse Compton scattering of the electrons by lower-energy photons. In the leptonic model interpretation, the latter comes either from the synchrotron radiation produced by the same population of electrons (Synchrotron Self-Compton, SSC, scenario) or from an external photon field. According to hadronic models, high-energy emission is due to processes involving the protons in the source. The investigation of blazar SED is important to determine which theoretical models are in action and to infer the parameters that drive the microphysics of the system. Multiwavelength (MWL) long-term monitoring of blazars is key since the SED modelling over time allows the study of the radiative processes during different states. The blazar 1ES 1959+650 represents an ideal laboratory for that, being bright at all the wavelengths and located at low redshift (z= 0.047) allowing its detection in the TeV band. Also, it underwent some flaring episodes in the past. A long-term MWL monitoring of 1ES 1959+650 is ongoing under the coordination of the MAGIC collaboration. During the last years, the source is experiencing its lowest state ever reached, mainly at very high energies. This contribution presents the MAGIC+MWL observations of the last 3 years, and the preliminary study focusing on an SSC interpretation of the data.

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1. Introduction

Blazars are Active Galactic Nuclei (AGN) with a relativistic jet raised from the central black hole that points in the observer's direction. The blazar' spectral energy distribution (SED, νF_ν as a function of ν, with ν being the frequency of photons and F_ν the frequency-dependent energy flux) is dominated by relativistic jet emission which extends from the radio band up to the TeV one. The SED shape of blazars is characterised by two bumps, the low-energy one peaking in the sub-millimetre to the X-ray regime and the high-energy one at around MeV energies.

Well-established theoretical models predict that the low-energy part of the spectrum, from radio to X-rays, is produced by relativistic electrons accelerated in the magnetic field of the jet, emitting synchrotron radiation. Depending on the frequency of the synchrotron peak (ν_{peak}) blazars are divided in low-, intermediate-, and high-synchrotron-peaked (LSP, $\nu_{peak} < 10^{14}$ Hz, ISP, $10^{14} < \nu_{peak} < 10^{15}$ Hz, and HSP, $\nu_{peak} > 10^{15}$ Hz, respectively) [1]. The origin of the emission at the high-energy part of the spectrum is still discussed. According to leptonic models, this can be due to inverse Compton (IC) interactions between the low-energy synchrotron photons with the relativistic electrons responsible for the synchrotron peak (synchrotron self Compton, SSC). In some sources, external regions provide the photon fields for IC interactions with the relativistic particles. According to hadronic models instead, the hadronic component of the jet plays a not negligible role in the radiation output of blazars at high energy. Both proton-photon interactions and proton synchrotron mechanism are assumed as possible radiative processes producing the second bump of the SED [11].

1ES 1959+650 is an HSP blazar classified as a BL Lac, namely blazars showing a featureless optical spectrum with nearly no emission lines. The source is located at a redshift 0.047 [9]. In agreement with typical blazar's behaviour, 1ES 1959+650 emission continuously varies across all the bands of the electromagnetic spectrum with different timescales. Due to its vicinity to us and its brightness at all the bands, the source has been intensively monitored from several facilities and the monitoring data have allowed the interpretation of the SED at different stages of the source lifespan.

The first outstanding event from 1ES 1959+650 was reported by the Whipple and High Energy Gamma Ray Astronomy (HEGRA) experiments which detected two strong TeV flares separated by one month from each other [e.g., 2]. The second of the two had no X-ray high-state counterpart at other wavelengths, so it is called the orphan flare. The absence of X-ray emission simultaneous to the TeV one challenges the predictions on the SSC model, according to which the very-high-energy (VHE, E > 100 GeV) and X-ray emission are both produced by the same population of electrons. Even more interestingly, the AMANDA neutrino observatory detection of two neutrinos simultaneously with orphan flare [4] would favour the hadronic scenario instead of the leptonic one, since high-energy neutrinos are among the byproducts of proton-photon collisions. However, the statistical significance of the detection is low and this makes the source an unconfirmed neutrino emitter candidate.

Since 2015 1ES 1959+650 is monitored at VHE by the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) Collaboration. During the MAGIC monitoring, in 2016, a new extreme flaring episode, with a photon flux exceeding 3 Crab units (CU), occurred [6]. This was followed by lower-intensity flaring activity over 2017 and 2018, after that, in 2019, the source entered its lowest state at VHE, with a photon flux lower than 0.6 CU [7]. The interchange of VHE low and high states underlies modifications in the main players of the emission mechanisms, such as the magnetic field and electron energy distribution in an SSC scenario. The rich amount of multi-year MWL data of 1ES 1959+650 has allowed the interpretation of the SED with different emission mechanisms, with the SSC models being the most effective ones, but the overall scenario is still unclear.

In this work, we focus on the MWL observations of 1ES 1959+650 from 2020 to 2022 and we describe the analysis approach based on a SSC scenario.

2. MWL data

In this section, the MWL data are presented.

MAGIC The MAGIC Collaboration operates a two-telescope system which exploits the Imaging Atmospheric Cherenkov (IACTs) technique to detect gamma-ray photons. MAGIC telescopes are located about 2200 meters above sea level, at the Roque de los Muchachos observatory of La Palma (Canary Islands). 1ES 1959+650 is observed over a zenith range from 35° to 66°at maximum. In this work we analyze three years of MAGIC observation, from June 2020 to August 2022, consisting of a total of about 100 hours of good-quality data. About half of the total hours of observations have been taken during the no-moon time, the other half hours are affected by the presence of the moonlight. Data collected under moonlight conditions have been properly handled following [3]. The data reduction was performed with the MAGIC analysis software MARS [13].

Fermi-LAT The Large Area Telescope (LAT) instrument, on board the Fermi Gamma-ray Space Telescope, observes the gamma-ray energy range between 20 MeV and 300 GeV. Thanks to the LAT, operating sky scans every three hours, continuous monitoring of gamma-ray sources is guaranteed. In this work, we included Fermi-LAT data overlapping the MAGIC data periods. The energy range adopted is 0.3-300 GeV and the temporal binning is of 7 days.

Swift-XRT and UVOT The satellite Neil Gehrels Swift Observatory hosts the X-Ray Telescope (XRT), which observes in the energy range of 0.2-10 keV, and the Ultraviolet Optical Telescope (UVOT) which is equipped with ultraviolet and optical band filters (UVW1, UVM2, UVW2, and U, B, V), observing at wavelengths from 170 to 650 nm. 1ES 1959+650 is regularly monitored by the Swift satellite and the data are public and available. Both Swift XRT and UVOT data from June 2020 to August 2022 are analyzed in this work.

Tuorla and KAIT 1ES 1959+650 has been observed in the optical R-band using the 1.03 m telescope at Tuorla Observatory, in Finland, as part of the Tuorla Observatory blazar monitoring. Simultaneous monitoring in the unfiltered optical band, which correspond roughly to the R band, is provided by the Katzman Automatic Imaging Telescope (KAIT).

OVRO At 15 GHz frequency, 1ES 1959+650 is monitored by the single-dish radio telescope operated by the Owens Valley Radio Observatory (OVRO) in California, US. OVRO observations and data reduction are reported in [10].

TELAMON The 100-m Effelsberg single-dish radio telescope monitors 1ES 1959+650 at multiple frequencies, from 14 GHz to 42 GHz, as part of the TeV Effelsberg Long-term Agn MONitoring (TELAMON). The monitoring program is illustrated in [5].

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VLBI The 43 GHz public very-long-baseline interferometry (VLBI) data of 1ES 1959+650 are provided by the Boston University Blazar Group which led the Large VLBA Project BEAM-ME. VLBA stands for *very-long-baseline array*, which is an array of ten antennas located in America working as an interferometer.

3. Variability and SED study

As typical for blazars, 1ES 1959+650 varies at all the wavelengths with different timescales, going from the timescale of hours, at VHE, to months, at the radio band. We characterise temporal variations and structures present in the MWL light curve by exploiting the Bayesian Blocks algorithm [8]. This algorithm is based on constructing optimal time intervals, the blocks, within which the emitted light from the source can be assumed as constant. The subdivision in blocks is based on a Bayesian approach. The algorithm starts with a first split in blocks of minimum duration and then proceeds with the iterative merging of adjacent blocks. The process continues until the introduction of a new block would not improve the model's likelihood. After multiple trials, the priors which enter the power law describing the number of time intervals (see function (3) in [8]) are adjusted to represent the variability in each light curve. To do that, we searched for a compromise between too few time bins that clearly combine different states and a too large number of time bins that closely follow the trend of the point-wise light curves, not providing then an actual split of the data.

The large MWL dataset gives us the opportunity to investigate the SED temporal changes of 1ES 1959+650. We apply the Bayesian Blocks analysis to divide the data into different time bins in which to perform the SED modelling and interpretation. At high energy, we usually need to integrate data due to the low statistic available. In this context, the Bayesian Blocks approach provides us with a tool to identify which data can be merged avoiding the averaging of different states of the source.

The results at low energies, from the X-ray down to the optical band, show that the instruments can detect finer structures with respect to the HE and VHE bands. This is due to the larger statistic available at the X-ray, UV and optical bands. The MWL light curve shows that the source is still in an overall low state as in 2019, both at VHE and at the other wavelengths. This is also confirmed by the Bayesian Blocks algorithm results. It appears indeed that, despite the source dramatically varying at all the wavelengths, no major outbursts as the 2016 one occurred over the period from 2020 to 2022. All the peaks are indeed almost consistent with each other.

Multiple minor flares can be identified in the optical light curves in a time range of about 100 days, from MJD 59400 to MJD 59600. However, the flux intensity in this observing period is still lower than the previous one (see the fifth panel of Fig 2 in [7]). A spectral variability at the X-ray band has also been reported by [12], in agreement with our result. The XRT data analysed in [12] partially overlap the time range of this work. The Fermi-LAT light curve has extremely low statistics due to the 7-day binning. We performed the SED modelling in each of the time bins identified in the MAGIC light curve using averaged spectra. At HE, we used the corresponding averaged spectrum while for the lower energy bands, we selected a one-day spectrum for each corresponding VHE block. This is done to avoid the merging of different states of the source since the variability at lower energies is detected on shorter timescales with respect to the VHE band.

We adopted a one-zone SSC model approach to describe the observational data. According to the one-zone models, the broadband emission comes from a single spherical compact blob. In the radio band, the extended jet emission is not resolved, it then represents a not negligible contribution to the total emission. For this reason, radio data are not included in the SED modelling.

The preliminary results of the SED modelling analysis in most of the time bin indicate that the low state 1ES 1959+650 can satisfactorily be described by an SSC model, with model parameters in agreement with previous studies.

4. Summary

We analysed the MAGIC+MWL data of the HSP BL Lac 1ES 1959+650, from 2020 to 2022. In this period the source is experiencing its lowest state ever reached. Modelling the observational points in the blazar SED plays a crucial role in distinguishing between leptonic and hadronic models. Moreover, SED modelling enables us to deduce the physical parameters, such as the ones describing the electron population's energy distribution shape, under various interpretation frameworks. Performing the SED analysis in a peculiar phase of the source, when it is in an overall low state allows us to understand the emission processes in action and to compare the case with the flaring states for which a few studies are available. In this work, we used a Bayesian Block approach in order to split the VHE data into time bins in which to study the SED. Most of the time bin SEDs can be well described assuming a SSC scenario. In a coming publication, the details on the SED results and on the alternative models assumed when an SSC model is not adequate will be presented.

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