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Long-term monitoring of the radio-galaxy M87 in gamma-rays: joint analysis of MAGIC, VERITAS and Fermi-LAT data

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M87 was discovered in the very-high-energy band (VHE, E > 100 GeV) with HEGRA in 2003, long before its emission was detected in the high-energy band (HE, E > 100 MeV) with Fermi-LAT in 2009, opening the window to a new family of extragalactic sources with tilted jets. After a series of major VHE flares in 2005, 2008, and 2010, which were detected in multiple bands, the source has been found in a low activity state, interrupted only by comparatively smaller-scale flares. MAGIC and VERITAS, two stereoscopic Cherenkov telescope arrays located at Roque de los Muchachos Observatory (Canary Islands, Spain) and the Fred Lawrence Whipple Observatory (Arizona, US), have monitored M87 continuously and in coordination for more than 10 years. In this work, we present the data for 4 years of MAGIC and VERITAS observations corresponding to 2019, 2020, 2021 and 2022. The resulting light curves are shown in daily and monthly scales where no significant variability is observed. In addition, we show the first joint analysis using combined event data from the two VHE instruments and Fermi-LAT to compute the spectral energy distribution.

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PoS(ICRC2023)572

1. Introduction

M87, also known as Messier 87, is a giant elliptical radio galaxy located in the Virgo Cluster, approximately 16 Mpc away [1] and, it is classified as a Fanaroff-Riley-I-type (FR I) galaxy [2]. The galaxy is powered by a supermassive black hole with a mass of (6.5 ± 0.7) $\times 10^9$ $M_\odot$ [3]. The jet, which extends to $\geq 30''$ [4], is misaligned with an angle between 15 ° to 25 ° [5, 6] with respect to our line of sight and has been resolved in the radio, optical and X-ray bands [7, 8].

M87 was first discovered in the very-high-energy band (VHE, E > 100 GeV) by the HEGRA collaboration in 2003 [9] and was later confirmed as a VHE emitter by H.E.S.S, MAGIC and VERITAS [10–12]. In 2009, Fermi-LAT also detected M87 in the high-energy band (HE, E > 100 MeV) [13]. These observations established M87 as a HE and VHE gamma-ray emitter and opened the window to a new family of active galactic nuclei (AGN) with misaligned jets.

As of today, the source has been found in three different episodes of flare activity in the VHE band, in 2005, 2008 and 2010 [10–12, 14], and in a quiescent low flux state since 2010 [15, 16] with the exception of smaller-scale flares.

In this context, MAGIC and VERITAS telescopes have periodically and in coordination monitored M87 since the last high activity period for more than 10 years. This data provides a unique opportunity to understand the evolution of the VHE emission of M87 during a low flux state.

2. The MAGIC and VERITAS Telescopes

MAGIC and VERITAS are two stereoscopic Imaging Atmospheric Cherenkov Telescopes (IACTs) arrays located at the Roque de los Muchachos Observatory (Canary Islands, Spain) and the Fred Lawrence Whipple Observatory (Arizona, US) respectively. The telescopes have been designed to detect the VHE gamma-ray emission from different galactic and extragalactic sources. The detection technique relies on the measurement of the Cherenkov light produced by the interaction of the gamma rays with the atmosphere. The main characteristics of both instruments are summarized in Table 1.

Telescope	**Number of Telescopes**	**Diameter [m]**	**Camera FoV [deg]**	**Pixel FoV [deg]**	**Number of Pixels**	**Energy Range [GeV]**
MAGIC	2	17	3.50	0.10	1039	> 50
VERITAS	4	12	3.50	0.15	499	> 85

Table 1: Summary of the main MAGIC and VERITAS telescope parameters [17, 18].

3. MAGIC and VERITAS Datasets and Analysis Method

The M87 observations included in this work were performed from December to July of 2019, 2020, 2021 and 2022 respectively. The data were collected at zenith angles ranging from 15 ° to 50 ° and during dark and moonlight conditions. Then, only the data collected under good weather conditions were kept in the analysis. After the data quality cuts a total of 112 and 61 hours of effective observation time was obtained for MAGIC and VERITAS respectively. In addition, a summary of the effective observation time for each period and for both instruments is shown in Table 2.

The MAGIC data were analyzed using the standard stereo reconstruction software (MARS)[19]. This included the calibration, image cleaning and parametrization according to [20] for each MAGIC telescope individually. For moonlight data, a dedicated analysis was performed with optimized image cleaning parameters for the different Night Sky Background (NSB) levels [21]. Then, a Random Forests (RF) [22] technique with the stereoscopic parameters was used to reconstruct the energy, the arrival direction and to classify the nature of the primary. Further details about the MAGIC stereo analysis can be found in [17].

In the case of VERITAS, data were analyzed with the one of the standard event reconstruction pipelines, `Eventdisplay` [23], and cross-checked with the other standard pipeline, `VEGAS` [24]. In both cases, this included calibration, image cleaning, trace integration, image parameterization, and reconstruction of the energy and arrival direction of gamma-ray-like events.

After separate analysis within the individual collaborations, the data were exported to the DL3 format with the gamma-ray-like events and the associated instrument response functions, and independently analyzed by gammapy [25]. Then, the gammapy results were compared with the native ones to check the compatibility between the different analysis pipelines.

Year	$T_{\mathrm{Eff}}^{\mathrm{MAGIC}}$ **[h]**	$T_{\mathrm{Eff}}^{\mathrm{VTS}}$ **[h]**
2019	40	7
2020	11	4
2021	35	20
2022	22	30
2019-2022	112	61

Table 2: Summary of the M87 effective observation time from 2019 to 2022 by MAGIC and VERITAS.

4. Results

In this section, results from the MAGIC and VERITAS observations corresponding to the period ranging from 2019 to 2022 are reported. This includes the study of the VHE variability by the two instruments and the characterization of the spectral energy distribution (SED) by MAGIC, VERITAS and Fermi-LAT.

4.1 Light Curves

The variability of the VHE gamma-ray emission of M87 is first studied for energies E > 350 GeV. Results are shown in daily and monthly scales in Figures 1 and 2 respectively. The daily and monthly light curves do not show a significant variability for MAGIC and VERITAS observations. This is better investigated by computing the mean integral flux, which is obtained by a fit to a constant to the monthly binned light curves. Results correspond to $(1.07 \pm 0.13) \times 10^{-12}$ cm^{-2}s^{-1} ($\chi^2/d.o.f = 1.98$) and $(0.96 \pm 0.13) \times 10^{-12}$ cm^{-2}s^{-1} ($\chi^2/d.o.f = 1.90$) for MAGIC and VERITAS respectively, as can be seen in Figure 2. The M87 emission state between 2019 and 2022 is clearly different from the flaring periods in 2005, 2008, and 2010 [11, 12, 14], but compatible with previous measurements performed during the low emission state [15].

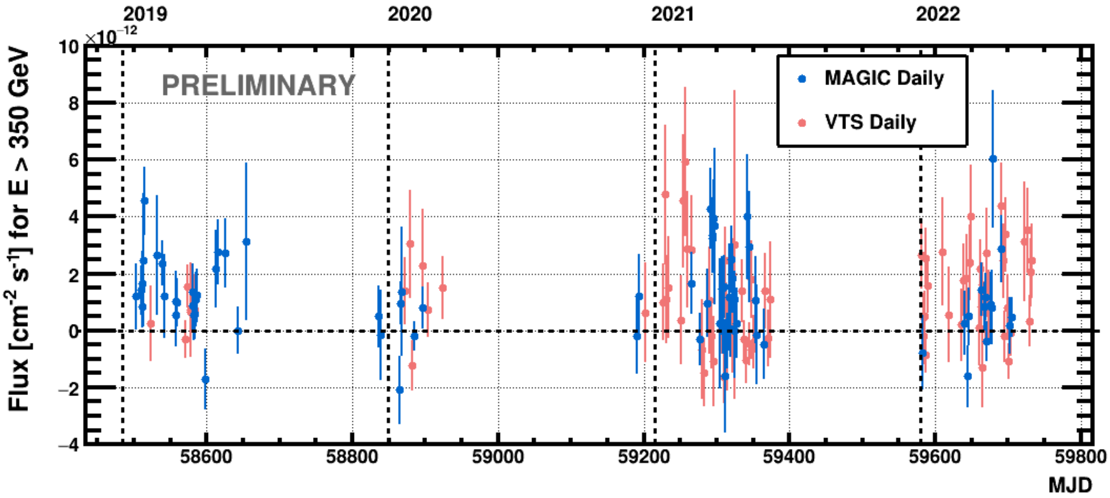

Figure 1: Daily light curves from 2019 to 2022 from MAGIC (blue points) and VERITAS (red points).

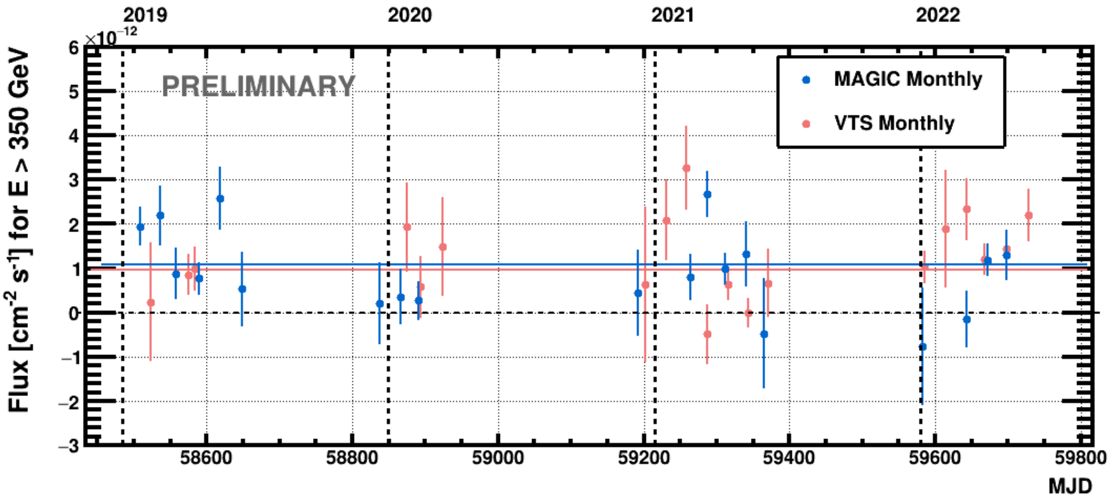

Figure 2: Monthly light curves from 2019 to 2022 from MAGIC (blue points) and VERITAS (red points). The mean integral flux is obtained by a fit to a constant to the monthly light curves for MAGIC (blue line) and VERITAS (red line).

4.2 Spectral Energy Distribution

The first joint analysis using combined event data from the two VHE instruments and Fermi-LAT is presented in Figure 3. The individual spectra, blue for MAGIC, red for VERITAS, and purple for Fermi-LAT, can be well described by a power-law of the form $E^2 dN/dE = f_0 (E/E_0)^{\Gamma}$ with f_0 the flux normalization, E_0 the energy normalization and Γ the spectral index. The flux normalization, f_0, corresponds to $(3.64 \pm 0.41) \times 10^{-13}$, $(3.66 \pm 0.36) \times 10^{-13}$ and $(1.32 \pm 0.21) \times 10^{-8}$ cm^{-2}s^{-1}TeV^{-1} for MAGIC, VERITAS and Fermi-LAT respectively. The energy normalization,

E_0, is 1 TeV for MAGIC and VERITAS and 10 GeV for Fermi-LAT. Finally, the spectral indices, Γ, stand for -2.58 ± 0.09, -2.33 ± 0.10 and -2.19 ± 0.10. The observed spectra are not significantly affected by the extragalactic background light (EBL) absorption due to the proximity of M87.

The joint fit, shown in Figure 3 as a gray band, spans from below 1 GeV to more than 10 TeV, and can also be described by a power-law with $f_0 = (1.25 \pm 0.08) \times 10^{-8}$ cm^{-2}s^{-1}TeV^{-1}, $E_0 = 10$ GeV and $\Gamma = -2.28 \pm 0.02$. The spectral index from the joint analysis reported in this work improves the statistical uncertainties obtained with the individual analysis, and it is also in good agreement with previous measurements performed during the low activity state of M87 [15, 16].

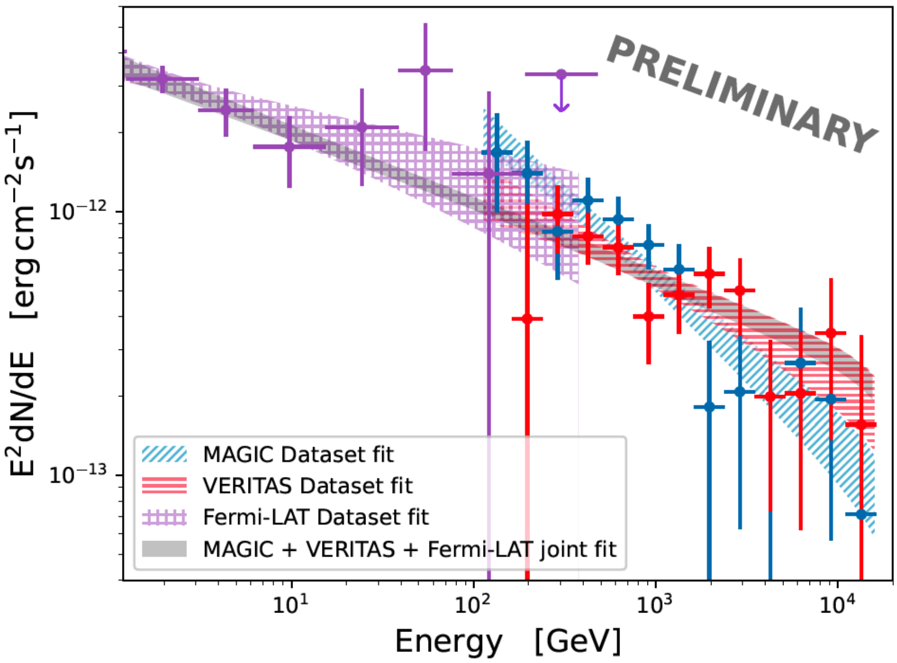

Figure 3: Spectral energy distribution between 2019 and 2022 combining data from MAGIC (blue points), VERITAS (red points) and Fermi-LAT (purple points). The fit to the MAGIC (blue band), VERITAS (red band), and Fermi-LAT (purple band) can be described by a power law. The joint fit (gray band) can be also described by a power-law.

5. Conclusions

In this work, the M87 observations performed by MAGIC and VERITAS during 2019 to 2022 have been presented. A total of 112 and 61 hours of effective observation was obtained for MAGIC and VERITAS repectively including dark and moonlight conditions.

First, the light curves for both instruments and for the whole dataset have been shown. No significant variability is observed at daily and monthly scales. Results are clearly different from the three periods of flare activity and compatible with previous low activity state measurements.

Then, the analyses on the individual spectra for MAGIC, VERITAS and Fermi-LAT together with the first joint analysis have been performed with gammapy. Results on the joint analysis show that the data, which spans from below 1 GeV to 10 TeV, can be described by a power-law with index

-2.28 ± 0.02. Results are compatible with previous measurements of M87 during a low activity state and, also, improve the statistical uncertainties obtained with the individual analysis.

The extension of the results presented in this work to more years could provide new insights to understand the evolution of the M87 VHE emission, and provide a denser sampling of the source state than what would be obtained for a single experiment.

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