M87: The 2010 very high energy gamma-ray flare & 10 years of multi-wavelength observations

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Abstract: The giant radio galaxy M 87 with its proximity, famous jet, and very massive black hole provides a unique opportunity to investigate the origin of very high energy (VHE; E>100 GeV) gamma-ray emission generated in relativistic outflows and the surroundings of super-massive black holes. M 87 has been established as a VHE gamma-ray emitter since 2005. The VHE gamma-ray emission displays strong variability on timescales as short as a day. In this paper, results from a joint VHE monitoring campaign on M 87 by the MAGIC and VERITAS instruments in 2010 are reported. During the campaign, a flare at VHE was detected triggering further observations at VHE (H.E.S.S.), X-rays (Chandra), and radio (43 GHz VLBA). The excellent sampling of the VHE gamma-ray light curve enables us to derive a precise temporal characterization of the flare: the single, isolated flare is well described by a two-sided exponential function with different flux rise and decay times. While the overall variability pattern of the 2010 flare appears somewhat different from that of previous VHE flares in 2005 and 2008, they share very similar timescales (∼day), peak fluxes, and VHE spectra. 43 GHz VLBA radio observations of the inner jet regions indicate no enhanced flux in 2010 in contrast to observations in 2008, where an increase of the radio flux of the innermost core regions coincided with a VHE flare. On the other hand, Chandra X-ray observations taken 3 days after the peak of the VHE gamma-ray emission reveal an enhanced flux from the core. The long-term (2001-2010) multi-wavelength (MWL) light curve of M 87, spanning from radio to VHE and including data from the Fermi-LAT, HST, LT, VLA and EVN, is used to further investigate the origin of the VHE gamma-ray emission. No unique, common MWL signature of the three VHE flares has been identified yet.

Keywords: galaxies: active – galaxies: individual (M 87) – gamma rays: observations – galaxies:jets; nuclei – radiation mechanisms: non-thermal.

1 Introduction

The giant radio galaxy M 87 provides a unique environment to study relativistic plasma outflows and the surrounding of supermassive black holes (SMBH). Its prominent jet [1] is resolved from radio to X-rays, displaying complex structures (knots, diffuse emission, [2]), strong variability [3], and superluminal motion [4] (Fig. 1, [5]). With its proximity (16.7 ± 0.2 Mpc) and its very massive black hole of $M_{\rm BH} \simeq (3-6) \times 10^9\,{\rm M}_\odot$ high-resolution radio observations enable one to directly probe structures with sizes down to < 200 Schwarzschild radii.

Evidence for very high energy (VHE; $E > 100$ GeV) γ-ray emission from M 87 was reported by the HEGRA collaboration in 2003 [6]. Up to now, three episodes of enhanced VHE activity have been detected from M 87. The first one, in 2005 [7], occurred during an extreme radio/optical/X-ray outburst of the jet feature HST-1 [3], which has been discussed as a possible site for the VHE emission [8]. During the second flaring episode, in 2008, HST-1 was in a low flux state, but radio measurements showed a flux increase of the core region within a few hundred Schwarzschild radii of the SMBH, suggesting the direct vicinity of the SMBH as the origin of the VHE emission [10]. This conclusion was further supported by the detection of an enhanced X-ray flux from the core region by *Chandra*. The angular resolution of ground-based VHE instruments[1] does not allow for a direct determination of the origin of the VHE emission in the inner kpc structures.

The third episode of increased VHE activity occurred in 2010 during a joint VHE monitoring campaign by MAGIC and VERITAS. The detection of the high state triggered further multi-wavelength (MWL) observations by the Very Long Baseline Array (VLBA), *Chandra*, and other instruments. Here we highlight the results of this campaign and

1. Typically, ∼0.1 degree per event, corresponding to ∼ 30 kpc projected size.

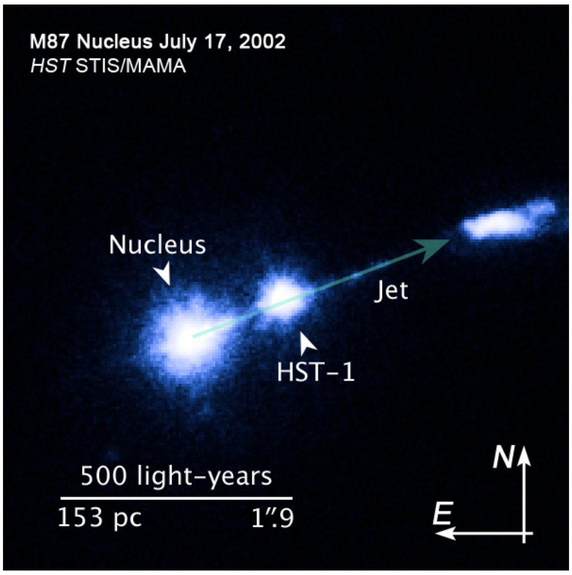

Fig. 1: Hubble Space Telescope (HST) image of M 87. *(Illustration Credit: NASA, ESA, and Z. Levay, STScI; Credit: NASA, ESA, and J. P. Madrid, McMaster University)*

briefly discuss implications. A more thorough discussion can be found in [11].

2 The 2010 VHE flare

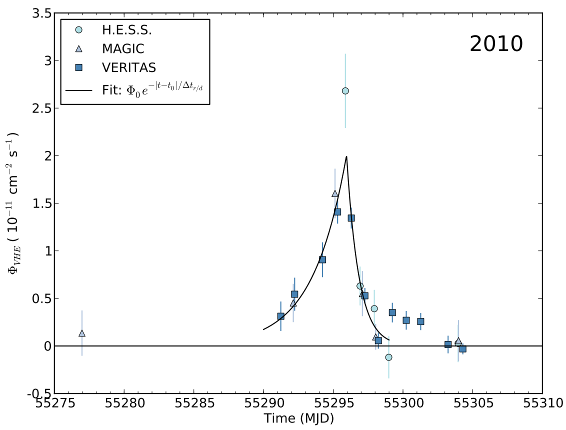

Fig. 2: VHE light curve of M 87 zoomed on the 2010 flare. Also shown are the results of the fit of an exponential function to the data.

During the 2010 monitoring campaign, two episodes of enhanced VHE γ-ray emission have been detected. The first episode took place in Feb. 2010, where a single night of increased activity was detected by MAGIC. VHE follow-up observations did not reveal further activity. The second episode took place in Apr. 2010 and showed a pronounced VHE flare detected by several instruments, triggering further MWL observations.

The VHE activity of this second flaring episode is concentrated in a single observation period between MJD 55290 and MJD 55305 ($\sim$15 days). This time period is exceptionally well covered by observations with 21 pointings by H.E.S.S., MAGIC, and VERITAS, resulting in an observation almost every night. The detected flare displays a smooth rise and decay in flux with a peak around MJD 55296 (April 9-10, 2010; see Fig. 2). The data points were fitted with an exponential function to determine the rise/decay times. In general, during nights with quasi simultaneous observations by different instruments, the measured fluxes are found to be in excellent agreement.

Compared to previous VHE flares detected in 2005 and 2008, the 2010 flare shows similar timescales and peak flux levels. The excellent sampling in 2010 also allowed, for the first time, to access rising and falling timescales of the flare.

3 VHE flares & MWL correlations

Over the last 10 years M 87 has been extensively monitored all across the electro-magnetic spectrum from radio to VHE (Fig. 3). This large data-set can be used to investigate MWL correlations and thereby probe the origin of the VHE γ-ray emission. In principle, many different γ-ray production models in relativistic jets could contribute to the VHE γ-ray emission in M 87. The detected short-term variability with timescales of the order of days and the limits on the location place strong constraints on possible scenarios [7], leaving the inner jet and the close vicinity of the SMBH as the most probable emission sites. In the following, the MWL behavior of the two most prominent features in the innermost structure of M 87, namely the HST-1 knot and the core, are discussed in the light of the VHE flaring activity.

HST-1 Between 2001 and 2008 the innermost bright feature in the jet resolved by the *HST* in the optical, HST-1, underwent a spectacular flare detected in radio, optical, and X-rays [3]. The flare displayed a relatively smooth rise over several years with a flux increase by more than a factor 50 in X-rays and optical. The flux peaked in the beginning of 2005 [12] around the same time when the enhanced activity level and the first short term variability had been detected at VHE [7]. HST-1 has been discussed as a possible site for the VHE γ-ray emission (see e.g. [8]). While the size of HST-1 as a whole is too large to account for the short-term variability detected at VHE (following causality arguments), high resolution VLBA radio observations resolve HST-1 into several, partially unresolved sub-structures. These sub-structures also display apparent superluminal motion up to $4.3\,c \pm 0.7\,c$. In combination with the detected synchrotron X-ray emission and strong polarization of the radio-to-optical continuum, this indicates that efficient in-situ acceleration of the radiating particles is taking place in compact sub-volumes of the HST-1 region, characterized by well-organized magnetic field and relativistic bulk velocities. On the other hand, during the 2008 and 2010 VHE flares HST-1 was in a low flux state without pronounced activity at radio or X-ray wavelengths, thus disfavoring it as the origin of the VHE γ-ray emission during these episodes. In a recent work, however, an intriguing time connection between the appearance of new superluminal blobs in HST-1 and the occurrence of VHE flares was found [9].

Core The direct vicinity of the SMBH and the jet base have been proposed as possible production sites of the VHE

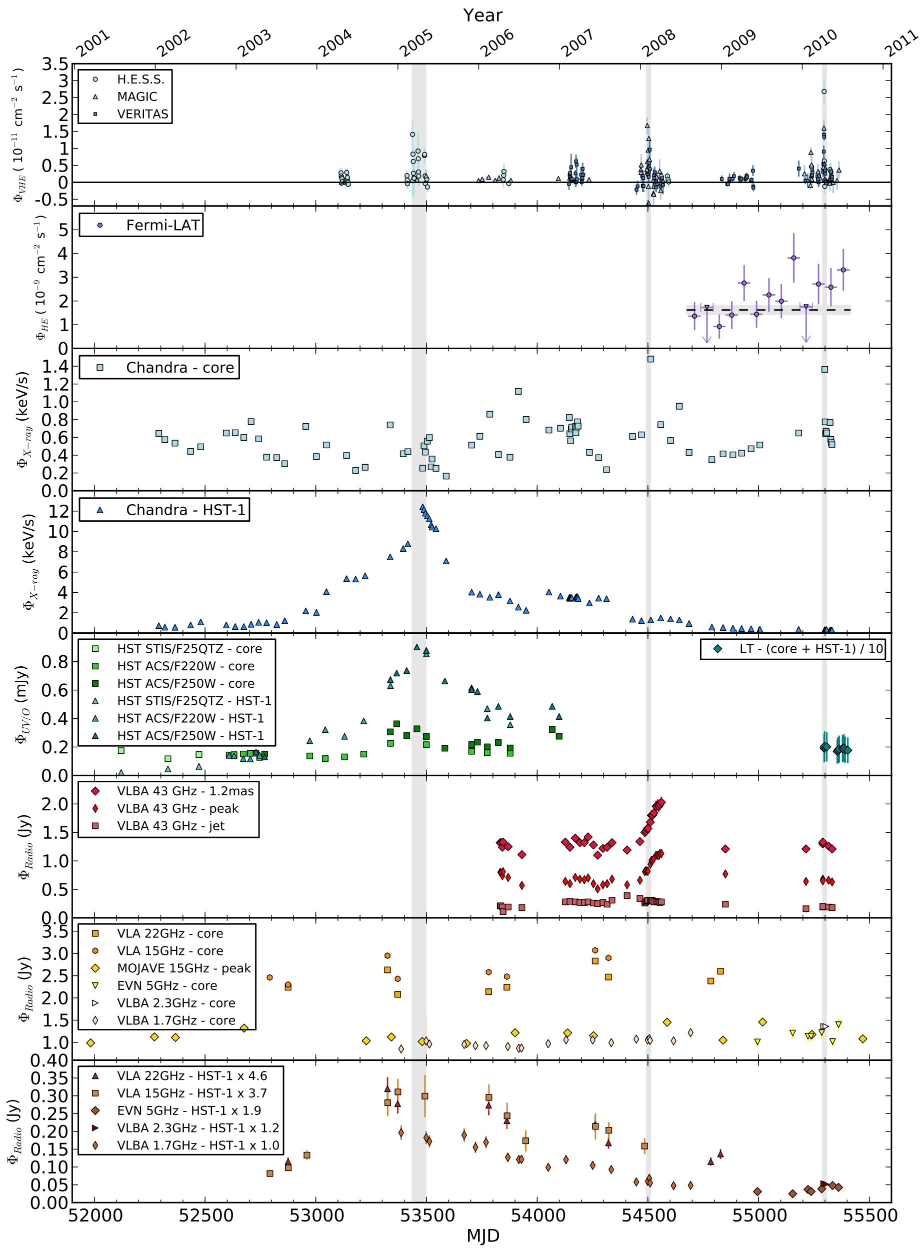

Fig. 3: Multi-wavelength light curve of M 87 from 2001 to 2011. The VHE γ-ray flux (top panel) is calculated above an energy threshold of 350 GeV (see text). Separate fluxes for the core and HST-1 are shown in cases where the instrument resolution is sufficient to separate the two components. Gray vertical bands mark the times of increased VHE activity in 2005, 2008, and 2010. The dashed line and the gray horizontal band in the 2nd panel marks the average flux (F> 1 GeV) measured by *Fermi*-LAT. The radio flux of HST-1 at different frequencies has been normalized to the 5 GHz flux assuming a spectrum $S_\nu \sim \nu^{-\alpha}$ with $\alpha = 0.6$. All flux errors shown are the 1 s.d. statistical errors except for the LT data where the uncertainty on the contribution from the galaxy is included in the error bars. For details on the data, the data analysis, and references see text.

γ-ray emission (see e.g [13, 14]). M 87 is only a weak IR source and, therefore, VHE γ-rays are most likely able to escape even from the close vicinity of the SMBH without suffering strong absorption due to $\gamma\gamma$-interactions [15]. The M 87 jet base has been imaged with VLBI with sub-mas resolution. It shows a resolved, edge brightened structure to within 0.5 mas of the core (0.04 pc) and indications for a weak counter-jet feature, suggesting that the SMBH lies within the central beam of the VLBI observations.

In 2008, densely sampled 43 GHz radio observation of the innermost jet regions revealed a flare of the radio core (flux increase of $\sim$ 30 %; [10]). At the same time, a flare at VHE and a subsequent enhanced X-ray flux from the core region were detected. The observed MWL variability pattern supported the interpretation that the VHE γ-ray emission likely originates from the close vicinity of the SMBH near the jet base [10].

In contrast, radio observations taken in 2010 contemporaneous with the VHE flare show no significantly enhanced radio flux from the core region (Fig. 3): VLBA 43 GHz

ToO observations triggered by the detection of the VHE flare indicate a stable flux state of the core (1.2 mas) and the inner jet (1.2 to 5.3 mas) at the previously detected flux levels. In addition, European VLBI Network (EVN) 5 GHz, VLBA 2.3 GHz, and MOJAVE 15 GHz measurements also show no indication of an enhanced radio flux state from the core in 2010. We note, however, that in a recent paper by [16] a slight increase by 10% (which is within the usual fluctuations of the data) of the radio core flux at 43/22 GHz in VLBA data was found coincident with the VHE flare in 2010.

On the other hand, *Chandra* X-ray observations of the core show an enhanced flux ~ 3 days after the peak of the VHE γ-ray emission in 2010 (see Fig. 3). The flux is enhanced by a factor ~ 2 for a single measurement and than drops back to a lower state less than two days later. The observed variability timescale is significantly shorter (by a factor ~ 10) then the shortest X-ray variability measured previously from the M 87 core. Further details on the *Chandra* X-ray data from 2010 can be found in [17].

4 Summary

The three VHE flaring episodes (2005, 2008 and 2010) show similar timescales and peak flux levels while the multiwavelength interpretation remains complicated. Moreover, a template of the VHE flare time evolution derived from the 2010 data does not fit well 2008 data. In general, no unique, common MWL signature of the three VHE flares has been identified yet. From the VHE long-term light curve the duty cycle for VHE flares is estimated to be $< 4 - 28\%$, depending on the assumed threshold flux defining a VHE high state. The VHE monitoring of M 87 continued but no further flare period has been detected yet [18].

VLBA 43 GHz observations, triggered by the detection of the VHE flare, show no indications for an enhanced radio emission from the jet base in 2010. This is in contrast to observations in 2008, where the detection of a radio outburst of the core contemporaneous with the VHE flare lead to the conclusion that the VHE γ-ray emission is likely produced in the direct vicinity of the SMBH [10]. *Chandra* X-ray observations, taken ~ 3 days after the peak of the VHE γ-ray emission, show a high flux state of the core region in 2010, supporting the interpretation that the VHE flare originates from the innermost jet regions. M 87 is also detected at GeV energies by *Fermi*-LAT [19] but no significant variability has been found so far.

The long term (2001-2010) light curve of M 87, spanning from radio to VHE, is investigated for a common MWL signature accompanying the three VHE flares. No unique signature is found. However, the two highest Chandra nucleus X-ray flux points were both measured close to the 2008/2010 VHE flares.

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This research has made use of data from the MOJAVE database that is maintained by the MOJAVE team [20].
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