

# A first joint M87 campaign in 2008 from radio to TeV gamma-rays

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**Abstract.** M87, the central galaxy of the Virgo Cluster, is the first radio galaxy detected in the TeV regime. The structure of its jet, which is not pointing toward the line of sight, is spatially resolved in X-ray (by Chandra), in optical and in radio observations. Time correlation between the TeV flux and emission at other wavelengths provides a unique opportunity to localize the very high energy gamma-ray emission process occurring in AGN. For 10 years, M87 has been monitored in the TeV band by atmospheric Cherenkov telescopes. In 2008, the three main atmospheric Cherenkov telescope observatories (H.E.S.S., MAGIC and VERITAS) coordinated their observations in a joint campaign from January to May with a total observation time of  $\approx 120$  hours. The campaign largely overlapped with an intensive VLBA project monitoring the core of M87 at 43 GHz every 5 days. In February, high TeV activities with rapid flares have been detected. Contemporaneously, M87 was observed with high spatial resolution instruments in the X-ray (Chandra) and radio band (VLBA). We discuss the results of the joint observation campaign in 2008.

**Keywords:** M87, VHE  $\gamma$ -rays, VLBI

## I. INTRODUCTION: M 87 IS A UNIQUE LABORATORY

Active galactic nuclei (AGN) are extreme extragalactic objects showing core-dominated emission (broadband continuum ranging from radio to X-ray energies) and strong variability on different timescales. A supermassive black hole (in the center of the AGN) surrounded by an accretion disk is believed to power the relativistic plasma outflows (jets) which are found in many AGN. Around 25 AGN have been found to emit VHE  $\gamma$ -rays ( $E > 100$  GeV). The size of the VHE  $\gamma$ -ray emission region can generally be constrained by the time scale of the observed flux variability [1], [2] but its location remains unknown.

The giant radio galaxy M 87 is located at a distance of 16 Mpc (50 million light years) in the Virgo cluster of

galaxies [3]. The angle between the plasma jet in M 87 and the line of sight is estimated to lie between  $20^\circ - 40^\circ$  [4], [5]. With its proximity, its bright and well resolved jet, and its very massive black hole with  $3 \times 10^9 M_\odot$ , [6], M 87 provides an excellent opportunity to study the inner structures of the jet, which are expected to scale with the gravitational radius of the black hole. Substructures of the jet are resolved in the X-ray, optical and radio wavebands [7] and high-frequency radio very long baseline interferometry (VLBI) observations with sub-milliarcsecond (mas) resolution are starting to probe the collimation region of the jet [8]. This makes M 87 a unique laboratory in which to study relativistic jet physics in connection with the mechanisms of VHE  $\gamma$ -ray emission in AGN.

VLBI observations of the M 87 inner jet show a well resolved, edge-brightened structure extending to within 0.5 mas (0.04 pc or 140 Schwarzschild radii  $R_s$ ) of the core. Closer to the core, the jet has a wide opening angle suggesting that this is the collimation region [8]. Along the jet, monitoring observations show both near-stationary components [9] (pc-scale) and features that move at apparent superluminal speeds [10], [11] (100 pc-scale). The presence of superluminal motions and the strong asymmetry of the jet brightness indicate that the jet flow is relativistic. The near-stationary components could be related to shocks or instabilities that can be either stationary or move more slowly than the bulk flow.

## II. TEN YEARS OF VHE $\gamma$ -RAY OBSERVATIONS OF M 87

Currently, there are about 25 extragalactic objects – all belonging to the class of AGN – that have been established as VHE  $\gamma$ -ray emitters by ground-based imaging atmospheric Cherenkov telescopes (IACTs), such as H.E.S.S., MAGIC and VERITAS. So far, all of them except the radio galaxies M 87, Centaurus A [12], and possibly 3C 66B [13] belong to the class of blazars (exhibiting a plasma jet pointing closely to our line of sight).

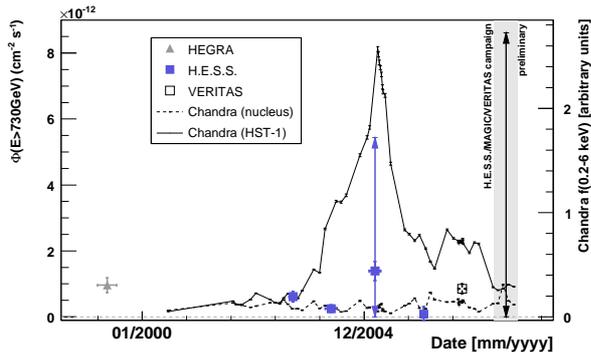


Fig. 1. The yearly averaged VHE  $\gamma$ -ray light curve  $\Phi(E > 730 \text{ GeV})$  of M87, covering the 10-year period from 1998-2008. The data points are taken from [14], [2], [17], [18]. Vertical arrows indicate the measured flux ranges for the given period (if variable emission was found). Strong variabilities ( $< 2$  days flux doubling times) were measured in  $\gamma$ -rays in 2005 and 2008. The Chandra X-ray light curves of the nucleus and HST-1 are also shown [29].

A first indication of VHE  $\gamma$ -ray emission ( $> 4\sigma$ ) from the direction of M87 in 1998/99 was reported by HEGRA [14]. The VHE  $\gamma$ -ray emission was confirmed by H.E.S.S. [2], establishing M87 as the first non-blazar extragalactic VHE  $\gamma$ -ray source. The reported day-scale variability strongly constrains the size of the  $\gamma$ -ray emission region. VERITAS detected M87 in 2007 [17] but with no variability. Recently, the short-term variability in M87 was confirmed by MAGIC in a strong VHE  $\gamma$ -ray outburst [18], [19]. The yearly averaged VHE  $\gamma$ -ray light curve of M87 for the past 10 years is shown in Fig. 1. The measured flux variability rules out large-scale emission from dark matter annihilation [20], or cosmic-ray interactions [21]. Leptonic [22], [23] and hadronic [24] jet emission models have been proposed to explain the TeV emission. The location of the VHE  $\gamma$ -ray emission is still unknown, but the nucleus [25], the inner jet [22], [24], [23], [28] or larger structures in the jet [26] have been proposed as possible sites. The 2005 VHE  $\gamma$ -ray flare (H.E.S.S.) was detected during an exceptional, several years lasting X-ray outburst of the innermost knot in the jet ‘HST-1’ [29], whereas the recent VHE  $\gamma$ -ray flaring activity (reported here) occurred during an X-ray low state of HST-1 (see Fig. 1). In this paper we report on a joint VHE observation campaign of M87 performed by H.E.S.S., MAGIC and VERITAS in 2008.

### III. THE 2008 CAMPAIGN ON M87

#### A. Joint H.E.S.S./MAGIC/VERITAS VHE observations

IACTs measure very high energy ( $E > 100 \text{ GeV}$ )  $\gamma$ -rays. The angular resolution of  $\sim 0.1^\circ$  of IACTs does not allow to resolve the M87 jet, but the time scale of the VHE flux variability constrains the size of the emission region, while flux correlations with observations at other wavelengths may enable conclusions on the location of the VHE  $\gamma$ -ray source. The current generation of instruments requires less than 10 h for the detection of a faint source with a flux level of a few percent

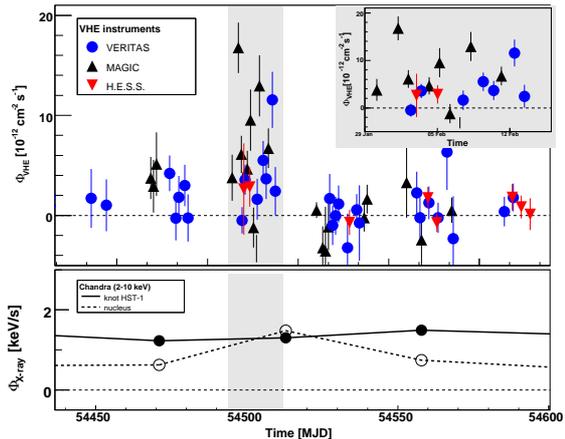


Fig. 2. *Top panel:* the night-by-night averaged VHE  $\gamma$ -ray light curve  $\Phi(E > 350 \text{ GeV})$  of M87, covering the 2008 joint campaign. Strong variability resulted in a detection of at least two flares by MAGIC and VERITAS (see the zoom in part of the campaign in the inset). The joint H.E.S.S./MAGIC/VERITAS campaign allowed for the unprecedented coverage at VHE  $\gamma$ -rays. *Bottom panel:* Corresponding Chandra measurements of the core and the HST-1 knot of M87.

of the Crab nebula flux. For a variable VHE  $\gamma$ -ray source like M87, a joint observation strategy as well as combining the results from several IACT experiments (and observations at other wavelengths) can substantially improve the scientific output (e.g. [30]). Coordinated observations with the VHE instruments H.E.S.S. [31], MAGIC [32] and VERITAS [33] result in: (1) an extended energy range by combining data sets taken under different zenith angles; (2) an extended visibility during one night, because the visibility of any given celestial object depends on the longitude of the experimental site; (3) an improved overall exposure and homogeneous coverage of the source; (4) alerts and direct follow-up observations in case of high flux states.

Among other AGN, the radio galaxy M87 is part of a multi-collaboration AGN trigger agreement between H.E.S.S., MAGIC and VERITAS. In order to achieve a best possible VHE coverage (especially during Chandra X-ray observations) a closer cooperation was conducted for the 2008 observations of M87: The collaborations agreed to have a detailed exchange/synchronization of their M87 observation schedules. Further on, information about the status of the observations (i.e. loss of observation time due to bad weather conditions, etc.) was exchanged on a regular basis between the shift crews and the observation coordinators.

M87 was observed by the three experiments for a total of  $> 120 \text{ h}$  in 2008 ( $\sim 95 \text{ h}$  after quality selection). The amount of data resulted in an unprecedentedly good coverage with  $> 50$  nights between January and May 2008.

#### B. Chandra X-ray observations

Chandra monitoring of M87 began in 2002 and continues to date. The angular resolution ( $\approx 0.8''$ ) allows resolving the large-scale jet structure, and in particular

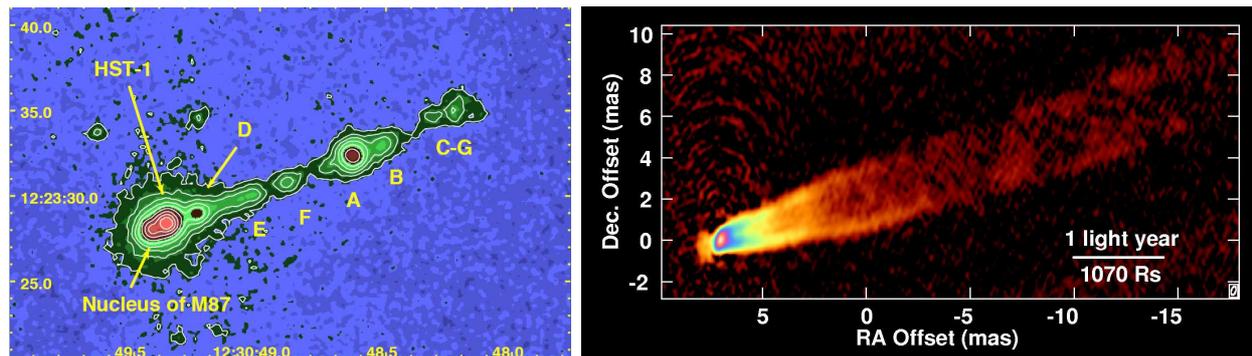


Fig. 3. Image of the M87 jet with high resolution instruments: Large-scale jet in X-ray obtained with Chandra (left). Inner jet in radio (43 GHz) obtained with VLBA (right).

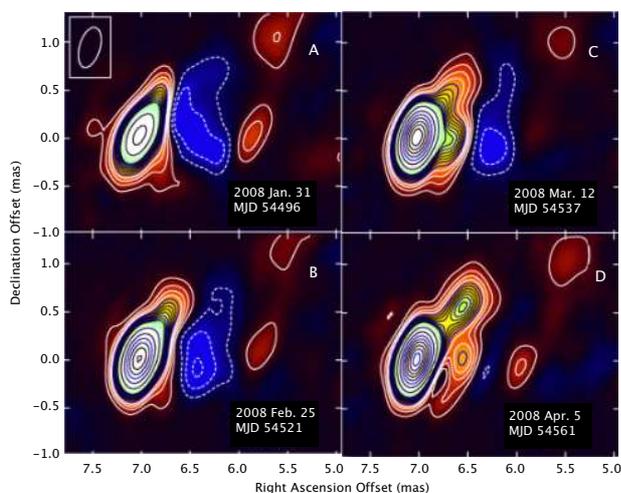


Fig. 4. VLBA images of M 87 at 43 GHz. (A)-(D): Sequence of difference images for observations during the period of the radio flare. These images have had an average image subtracted in order to show the effects of the flare. The average was made from eleven observations in 2007, outside the period affected by the flare. The contours are linear with 10 (white) at intervals of 7 mJy per beam followed by the rest (black) at intervals of 70 mJy per beam; negative contours are indicated by dashed lines. The sequence shows the significant rise in the core flux density and the appearance of enhanced emission along the inner jet.

to distinguish emission from the core and the innermost knot ‘HST-1’ (left panel in Fig. 3). During an observing season, M87 is observed every  $\sim 6$  weeks. That sampling allows detection of 1.5 month-scale variability. The most remarkable discovery of the monitoring campaign so far has been the giant flare of HST-1 [29], which reached its maximum intensity in 2005 (Fig. 1) when the TeV emission was detected in flaring state for the first time, suggesting HST-1 as the possible origin of the VHE emission [26]. Simultaneously, a huge optical flare was detected by the Hubble Space telescope [27]. Additional observations were taken in 2007 on shorter intervals to investigate short-time variability and possible correlation with VHE emission, which was unfortunately in a quiet state at that time.

### C. Radio: VLBA

Throughout 2007, M87 was observed at 43 GHz with the VLBA on a regular basis roughly every three weeks [15]. In January 2008, the campaign was intensified to one observation every 5 days. The resolution of the observations is unprecedented:  $0.21 \times 0.43$  milliarcseconds or  $30 \times 60$  Schwarzschild diameter of M87. The aim of this ‘movie project’ was to study morphological changes of the plasma jet with time. Preliminary analysis of the first 7 months showed a fast evolving structure, somewhat reminiscent of a smoke plume, with apparent velocities of about twice the speed of light. These motions were faster than expected so the movie project was extended from January to April 2008 with a sampling interval of 5 days.

### D. Results

In January 2008, the VHE  $\gamma$ -ray flux was measured at a slightly higher level than in 2007. MAGIC detected a strong flaring activity in February 2008 [18], [19], which led to immediate intensified observations by all three VHE experiments. VERITAS detected another flare about one week after the MAGIC trigger. The joint 2008 VHE  $\gamma$ -ray light curve clearly confirms the short-term variability reported by H.E.S.S. in 2005 [2]. During the 2008 VHE flaring activity, MAGIC observed flux variability above 350 GeV on time scales as short as 1 day (at a significance level of 5.6 standard deviations). At lower energies (150 GeV to 350 GeV) the emission was found to be compatible with a constant level [18], [19]. From March to May, M87 was back in a quiet state.

In 2008, the X-ray and VHE  $\gamma$ -ray data suggested a different picture compared to the 2005 flare (Fig. 1): HST-1 was in a low state, with the flux being comparable with the X-ray flux from the core. The core, however, showed an increased X-ray flux state in February 2008, reaching a highest flux ever measured with Chandra just few days after the VHE flaring activity.

VLBA measured a continuously increasing radio flux from the region of the nucleus ( $r=1.2$  mas) during the 2008 campaign, whereas in 2007 the flux was found to

be rather stable. Individual snapshots of the inner region of the jet are shown in Fig. 4. The observed radio flux densities reached at the end of the 2008 observations, roughly 2 months after the VHE flare occurred, are larger than seen in any previous VLBI observations of M 87 at this frequency, including during the preceding 12 months of intensive monitoring, in 6 observations in 2006 and in individual observations in 1999, 2000, 2001, 2002, and 2004 [16]. This suggests that radio flares of the observed magnitude are uncommon. The correlation study and the implication of the 2008 results on the VHE emission models are under investigation and will be published elsewhere.

#### IV. CONCLUSION AND OUTLOOK

The cooperation between H.E.S.S., MAGIC and VERITAS in 2008 allowed for an optimized observation strategy, which resulted in the detection and detailed measurement of a VHE  $\gamma$ -ray outburst from M87. Simultaneous Chandra observations, found HST-1, the innermost knot in the jet, in a low state, while the nucleus showed increased X-ray activity. This is in contrast to the 2005 VHE  $\gamma$ -ray flare, where HST-1 was in an extreme high state. The radio activity in 2007–2008, resolving the inner region of M87 down to some 10s Schwarzschild radii, allows for speculation about the origin of the VHE  $\gamma$ -ray emission. A model suggesting HST-1 to be the origin of the  $\gamma$ -ray emission seems less likely in the light of the 2008 result. Due to its proximity and the viewing angle of the jet, M87 is a unique laboratory for studying the connection between jet physics and the measured VHE  $\gamma$ -ray emission. To finally unravel the location/mechanism of the VHE  $\gamma$ -ray emission, future coordinated VHE observations (such as the 2008 campaign) are essential, together with simultaneous observations in the radio to X-ray (Chandra) regimes. Future joint observations could also lead to the detection of VHE  $\gamma$ -ray intra-night variability, which would further constrain the size of the emission region.

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