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VERITAS 2008–2009 MONITORING OF THE VARIABLE GAMMA-RAY SOURCE M 87


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ABSTRACT

M 87 is a nearby radio galaxy that is detected at energies ranging from radio to very high energy (VHE) gamma rays. Its proximity and its jet, misaligned from our line of sight, enable detailed morphological studies and extensive modeling at radio, optical, and X-ray energies. Flaring activity was observed at all energies, and multi-wavelength correlations would help clarify the origin of the VHE emission. In this paper, we describe a detailed temporal and spectral analysis of the VERITAS VHE gamma-ray observations of M 87 in 2008 and 2009. In the 2008 observing season, VERITAS detected an excess with a statistical significance of 7.2 standard deviations (σ) from M 87 during a joint multi-wavelength monitoring campaign conducted by three major VHE experiments along with the Chandra X-ray Observatory. In 2008 February, VERITAS observed a VHE flare from M 87 occurring over a 4 day timespan. The peak nightly flux above 250 GeV was (1.14 ± 0.26) × 10⁻¹¹ cm⁻² s⁻¹, which corresponded to 7.7% of the Crab Nebula flux. M 87 was marginally detected before this 4 day flare period, and was not detected afterward. Spectral analysis of the VERITAS observations showed no significant change in the photon index between the flare and pre-flare states. Shortly after the VHE flare seen by VERITAS, the Chandra X-ray Observatory detected the flux from the core of M 87 at a historical maximum, while the flux from the nearby knot HST-1 remained quiescent. Acciari et al. presented the 2008 contemporaneous VHE gamma-ray, Chandra X-ray, and Very Long Baseline Array radio observations which suggest the core as the most likely source of VHE emission, in contrast to the 2005 VHE flare that was simultaneous with an X-ray flare in the HST-1 knot. In 2009, VERITAS continued its monitoring of M 87 and marginally detected a 4.2σ excess corresponding to a flux of ~1% of the Crab Nebula. No VHE flaring activity was observed in 2009.

Key words: galaxies: individual (M87, VER J1230+123) – gamma rays: galaxies

Online-only material: color figures
1. INTRODUCTION

M 87 is an FR I radio galaxy located at a distance of 16.7 Mpc near the center of the Virgo cluster. It has been observed at all wavelengths ranging from radio to very high energy (VHE) gamma-rays. Its core is an active galactic nucleus (AGN) powered by a supermassive black hole of mass \((6.0 \pm 0.5) \times 10^9 M_\odot\) (Gebhardt & Thomas 2009; see the supporting material of Acciari et al. 2009 for mass corrected distance assumption), which is the source from which the first plasma jet emission was observed (Curtis 1918). Most of the known extragalactic VHE sources are blazars (TeVCat 2007). AGNs with a jet aligned close to the line of sight; in contrast, the jet of M 87 is misaligned. Apparent superluminal motion was observed in both the radio (Cheung et al. 2007) and optical (Biretta et al. 1999) bands for different features along the jet, constraining the jet orientation to be less than 30° from the line of sight at the location of the HST-1 knot, which is located 0′.86 from the core (Harris et al. 2009).

VHE emission from M 87 was first reported by the HEGRA collaboration at a statistical significance of 4.1σ during their 1998–1999 observations (Aharonian et al. 2003). This was confirmed by the HESS collaboration (Aharonian et al. 2006), which additionally reported year-scale flux variability. The observed variability provides a size constraint on the VHE emission production region and disfavors large-scale gamma-ray production models, such as the dark matter annihilation model (Baltz et al. 2000) and the interacting cosmic-ray proton scenario (Pfrommer & Ensslin 2003) which predict steady gamma-ray emission. However, the angular resolution of imaging atmospheric Cherenkov telescopes (IACTs) is insufficient to resolve any structure in M 87. Aharonian et al. (2006) also reported fast (2 day scale) variability during a high state of gamma-ray activity in 2005, which further constrains the VHE emission size and favors the immediate vicinity of the M 87 black hole as the VHE production site; on the other hand, Chandra X-ray observations at the time of the VHE flare indicated a different scenario. Strong flux variability from both the core and HST-1 in the energy range 0.2–6 keV has been detected by Chandra M 87 monitoring since 2002 (Harris et al. 2003). At the same period of the flare observed by HESS in 2005, Harris et al. (2008) reported an X-ray flux from HST-1 at more than 50 times the intensity observed in 2000, along with flaring activity observed in ultraviolet and radio wavelengths, suggesting the HST-1 knot as a more likely source of VHE emission than the core.

The All-Sky Monitor (ASM) on RXTE has provided daily monitoring of M 87 in the energy range 2–12 keV since 1996. However, ASM cannot resolve the core and the HST-1 knot over the past five years in the 0.2–6 keV range. The ASM/RXTE quick-look results do not show any correlated activity with VHE observations at shorter timescales, as a result of the limited sensitivity of ASM.

The proximity of M 87 and its misaligned jet enable high-resolution studies of its jet structures in radio, optical, and X-rays (Marshall et al. 2002; Perlmutter & Wilson 2005). The jet morphology is similar in those wavebands, and leptonic synchrotron radiation is favored as the process for non-thermal emission within the jet (Wilson & Yang 2002). Based on the multi-wavelength correlated activities and variability studies, the favored candidate for VHE emission is the small-scale (subarcsecond) jet region. Reimer et al. (2004) propose a synchrotron proton blazar model in which protons are accelerated to energies above EeV and emit gamma rays via muon/pion synchrotron or proton synchrotron radiation. However, this model requires a strong magnetic field to accelerate the protons to such high energies, and the predicted VHE spectrum is steeper than observed. Several leptonic models involving synchrotron and inverse Compton (IC) radiation have also been suggested, with the multi-component emission originating in the inner jet. There is the model by Georganopoulos et al. (2005) in which energetic electrons IC scatter off of synchrotron photons produced downstream in the decelerating jet, a scenario by Lenain et al. (2008) in which VHE emission is produced via the synchrotron self-Compton (SSC) process inside several similar homogenous compact components that contain more energetic electrons than the jet, and the model by Tavecchio & Ghisellini (2008) in which a fast-moving spine is surrounded by a slower-moving sheath producing VHE emission via external-Compton scattering. Single-component SSC emission is recently modeled by Abdo et al. (2009) with Very Long Baseline Array (VLBA) radio, Chandra X-ray, and Fermi-LAT 2009 data. However, comparing the model to archival non-flaring VHE data, it appears to underpredict the VHE emission.

The vicinity of the black hole (the core) has been suggested by Levinson (2000) and Neronov & Aharonian (2007) in the black hole magnetosphere model, in which gamma-ray photons are produced by electrons accelerated by the electromagnetic field of the black hole. The HST-1 knot, 0′.86 away from the core, has also been demonstrated as a possible location for jet reconfinement where photons can be upscattered to TeV energies via IC process (Stawarz et al. 2006). In 2008, the VHE gamma-ray experiments HESS, MAGIC, and VERITAS took part in a joint multi-wavelength monitoring campaign of M 87 along with Chandra (Bellicè et al. 2008). The VHE observations were closely coordinated in order to guarantee a reasonable coverage around the Chandra pointings and a well-sampled VHE light curve during the first half of 2008. During this joint monitoring campaign, MAGIC reported flaring activities during a 13 day observation period between January 30 (MJD 54495) and February 11 (MJD 54507), with day-scale variability occurring throughout the duration of the flare (Albert et al. 2008). Subsequently, the VERITAS collaboration triggered intensified observations of M 87, and detected a 4 day flare from February 9 (MJD 54505) to February 13 (MJD 54509). The VHE and Chandra X-ray light curves of the joint campaign, along with a coincident VLBA radio light curve, are presented in Acciari et al. (2009), which also includes a discussion on the radio/VHE gamma-ray correlation as evidence that the VHE emission originates from the core.

The VHE flux monitoring campaign continued in 2009 with MAGIC and VERITAS. In this paper, we present the results...
from two seasons (2008–2009) of VERITAS observations, along with a full analysis on the timescale of the flux variability, and a search for spectral variability in the 2008 data set when the VHE flaring activity was observed.

## 2. OBSERVATIONS AND ANALYSIS

VERITAS is an array of four 12 m diameter IACTs located at the Fred Lawrence Whipple Observatory on Mount Hopkins (31°40’ N, 110°57’ W) at an altitude of 1.3 km above sea level. Each telescope has a total area of 110 m$^2$ and an $f/D$ ratio of 1.0. Each telescope camera is equipped with 499 photomultiplier tubes, arranged in a hexagonal lattice covering a field of view (FOV) of $5\times5$. The array is sensitive from $\sim100$ GeV to more than 30 TeV, with an effective area of up to $10^4$ m$^2$ and an angular resolution of 0.1 $^\circ$ at 1 TeV (68% containment). VERITAS can detect a source with 1% Crab Nebula flux in less than 50 hr, and a source with 5% Crab Nebula flux in $\sim2.5$ hr. For more technical details of VERITAS, see Holder et al. (2006).

M 87 was observed with VERITAS for over 43 hr between 2007 December and 2008 May and over 25 hr between 2009 January and May, at a range of zenith angles from 19$^\circ$ to 41$^\circ$. All 2008 data and 81% of 2009 data used were taken with a three-telescope array. After eliminating observations in poor weather and those with an unstable trigger rate, 37 hr and 19 hr of good-quality live time remain in 2008 and 2009, respectively.

Shower images from all working telescopes are first corrected in gain and timing using parameters obtained from the nightly laser calibration data (Hanna et al. 2008). The images are then passed through a two-step cleaning process that retains pixels with a signal that is several times higher than the night-sky background level. Each shower image is then parameterized (Hillas 1985) and the shower direction is reconstructed using the stereoscopic technique (Hofmann et al. 1999). Events are then selected as gamma-ray-like if at least three camera images pass the standard cuts optimized for a 10% Crab Nebula flux source (Colin et al. 2008). All the observations were performed in “wobble mode” where M 87 was tracked with a 0.5 $^\circ$ offset relative to the camera such that the camera’s FOV contain both the source region and regions for background estimation. The on-source region is defined by a 0.1$^\circ$ radius circle centered on the M 87 core. All gamma-ray-like events within this region are summed as the ON count, and the background estimated from seven identically sized regions reflected from the source region around the camera center is summed as the OFF count (Berge et al. 2007). The ON and OFF counts are then used in Formula (17) of Li & Ma (1983) to calculate the significance of the excess. As a standard procedure in VERITAS, the results were confirmed by at least one independent analysis package (Daniel et al. 2008) which was presented in Acciari et al. (2009).
Throughout different activity levels, and there is no indication of a spectral cutoff. MAGIC (Albert et al. 2008), M 87 was marginally detected with 13.8 hr of live time at a flux of \( (3 \times 10^{-12}) \) cm\(^{-2}\) s\(^{-1}\) TeV\(^{-1}\), corresponding to the core, a linear test function of the form \( dN/dE = \Phi E^{-\Gamma} \), where \( \Phi \) is the flux and \( \Gamma \) is the photon energy distribution. Table 2 displays the power-law fit parameters for the core and pre-flare states.

Before the flare period (MJD 54448 — 54503), which included two nights immediately after the major flare observed by MAGIC (Albert et al. 2008), M 87 was marginally detected with 13.8 hr of live time at a flux of \((3.30 \pm 0.68) \times 10^{-12}\) cm\(^{-2}\) s\(^{-1}\) above 250 GeV. The 99% confidence interval for the flux during the pre-flare period (see slant-lined area between MJD 54448 and 54503 in Figure 1) is between \(1.55 \times 10^{-12}\) cm\(^{-2}\) s\(^{-1}\) and \(5.05 \times 10^{-12}\) cm\(^{-2}\) s\(^{-1}\). M 87 was observed for an additional 17.2 hr of live time after the flare period and was not detected. An upper limit of \(2.1 \times 10^{-12}\) cm\(^{-2}\) s\(^{-1}\) at 99% confidence level (Helene 1983) is established for the post-flare period, corresponding to 1.4% of the Crab Nebula flux. Assuming a normal distribution for the flux measurements, the flare flux is higher than the pre-flare flux at 99.95% confidence level, and the pre-flare flux is higher than the post-flare flux at 99.8% confidence level. All of the above calculations were performed under the assumption of a constant photon index of 2.50.

The spectra from different periods are plotted in Figure 2 and there is no indication of a spectral cutoff. The power-law fit parameters from the overall, flare, and pre-flare spectra are displayed in Table 2. No significant difference in photon index and photon energy distribution is found between the flare and pre-flare states.

To test if there is any correlation between the spectral flux and photon index measured during different activity levels corresponding to the core, a linear test function of the form \( \Gamma = p_0 + p_1 \times \log 10 \Phi_0 \) was fitted to past measurements by Aharonian et al. (2006) in 2004 and Acciari et al. (2008) in 2007, and the high/low states measured by Albert et al. (2008) and by VERITAS in 2008 (see Figure 3). The measurement by HESS in 2005 is excluded in the fit due to possible contamination from the HST-1 flare. The \( \chi^2/dof \) of the linear fit is 1.7/4 and the corresponding probability of a correlation between photon index and flux is 78.6%. The fit parameter \( p_1 \) is consistent with zero. Fitting a constant photon index gave a \( \chi^2/dof \) of 2.7/5 and a corresponding probability of 74.6%. No significant correlation is found between the photon index and the flux.

At the time of the flare detected by VERITAS, Chandra measured the core X-ray flux at a historical maximum, at 4.1\( \sigma \) above the mean core flux between 2000 and 2009, and exceeding the flux from the HST-1 knot (see Figures 1 and 4; Harris et al. 2009). The peak core X-ray flux measured by Chandra during the observation period of VERITAS was 2.3 times the average core X-ray flux, with the average calculated excluding this flare data point. While the HST-1 knot X-ray flux during this period fluctuated \( \pm 10\% \) from the average and is relatively steady when compared to the core emission. Figure 5 shows the fractional change per year (fpy) first presented in Harris et al. (2009). Around the 2008 VHE gamma-ray flare period, the Chandra core fpy is more variable than that of the Chandra HST-1 fpy measurement. The definition of fpy is repeated below (Harris et al. 2009):

\[
\text{fpy} = \frac{I_j - I_i}{I_i \Delta t}, \tag{1}
\]

\[
\sigma_{\text{fpy}} = \frac{1}{\Delta t} \times \frac{I_j}{I_i} \times \sqrt{\left( \frac{\sigma_1}{I_1} \right)^2 + \left( \frac{\sigma_2}{I_2} \right)^2}, \tag{2}
\]

where \( I \) is the X-ray intensity measured by Chandra and \( \Delta t \) is the time between the two intensity measurements in units of year. If the X-ray intensity is increasing (i.e., \( I_2 > I_1 \)), then \( i = 1 \) and \( j = 2 \); if the X-ray intensity is decreasing (i.e., \( I_2 < I_1 \)), then \( i = 2 \) and \( j = 1 \).

### 3.2. 2009

The VERITAS observations in 2009 resulted in 134 excess events at a significance of 4.2\( \sigma \). The \( \chi^2/dof \) of a constant rate fit to the entire data set is 23/18 and no significant variability was observed in the 2009 data set. The average flux above 250 GeV is \((1.59 \pm 0.39) \times 10^{-12}\) cm\(^{-2}\) s\(^{-1}\) assuming a photon index of 2.50. This corresponds to 1.1% of the Crab Nebula flux and is consistent with the reported Fermi-LAT spectrum (Abdo et al. 2009). The 2009 flux is below the 2008 pre-flare flux at the 98.5% confidence level, but above the 2008 post-flare flux at the 87.6% confidence level. Figure 5 shows the light curves of...
Figure 4. M 87 yearly VHE gamma-ray (Aharonian et al. 2003, 2006; Acciari et al. 2008; Albert et al. 2008) and X-ray fluxes (Harris et al. 2009). The VHE gamma-ray flux is for energy > 730 GeV due to the original flux scale used in the HEGRA paper. This yearly flux plot is first presented in Acciari et al. (2008) and is now updated with 2008 and 2009 data. Gray areas represent the range of variable VHE fluxes observed that year to give a more accurate picture of the flux level of M 87.

(A color version of this figure is available in the online journal.)

Figure 5. Upper panel: VERITAS night-by-night VHE gamma flux and Chandra X-ray flux from the core and from the HST-1 knot of M 87 in 2008 (Harris et al. 2009) and 2009. Lower panel: Chandra X-ray flux fpy, see the text for definition (Harris et al. 2009).

both 2008 and 2009 observed by VERITAS and the X-ray flux measured by Chandra for the core and the knot HST-1, along with the fpy of Chandra X-ray flux.

During the 2009 observation period, Chandra took a flux measurement every 40–50 days. The HST-1 flux measured by Chandra is steadily declining at a rate of 5%–10% when compared to the previous flux (ΔI/I). The core flux, however, is mostly increasing by as much as 18%. The lack of VHE activity during this period suggests a possible association between VHE flares and significant changes in the X-ray flux such as the one seen in 2008 where the core fpy is more variable than in 2009 (see Figure 5).

4. DISCUSSION

The proximity of M 87 and its misaligned jet have enabled the study of its jet morphology in a broad range of energies. Flaring activities from individual jet features have been observed in radio, optical, and X-rays in parallel (Cheung et al. 2007). Modeling of the particle acceleration yields several possible VHE emission origins. Even though the VHE gamma-ray technique cannot resolve individual features of M 87, the rapid variability reported by Aharonian et al. (2006) and Albert et al. (2008) has constrained the size of the VHE emission region to < 2.6δ R_s, where δ is the relativistic Doppler factor and R_s is the Schwarzschild radius of the M 87 black hole.
Aharonian (2007), and others have argued that acceleration of correlation between large X-ray flux changes and flaring Chandra of the knot. The fpy of the knot data and the fpy for the core in 2009 is smaller than Chandra VHE emission. Therefore, both the HST-1 and the core region remain as the possible origins of VHE emission.

In 2009, VERITAS detected M 87 similar to the 2008 pre-flare level. The X-ray timescale analysis is repeated for the 2009 Chandra data and the fpy for the core in 2009 is smaller than in 2008 during the VHE gamma-ray flare. The fpy of the knot HST-1 appeared to be negative throughout 2008 and 2009, and with no corresponding VHE gamma-ray flare. A similar analysis is not performed for the 2005 HESS flare due to contamination from the knot HST-1 in Chandra data.

The compactness of the particle accelerators operating in the vicinity of the supermassive black hole and the absence of a significant cutoff in the spectrum imply that the particle acceleration mechanism is highly efficient. Levinson (2000), Neronov & Aharonian (2007), and others have argued that acceleration mechanisms similar to those in pulsar magnetosphere models can also operate in the black hole magnetosphere. The black hole magnetosphere model and the two-zone leptonic models (Georganopoulos et al. 2005; Lenain et al. 2008; Tavecchio & Ghisellini 2008) can reproduce the VHE spectrum and the flux variability well. While no constraints can be placed on the VHE range of these models, since VERITAS and other VHE gamma-ray instruments did not observe a cutoff in the spectrum of M 87, the Fermi Gamma-ray Telescope, sensitive from MeV to GeV energies, can potentially provide constraints on the magnetic field strength and a measure of low-energy gamma-ray photon flux from the synchrotron/curvature radiation. Abdo et al. (2009) presented the first year of Fermi-LAT observations of M 87 in 2009 during its quiescent state. Continual monitoring in all wavelengths is essential for the modeling of the spectral energy distribution of M 87. Future instruments such as CTA/AGIS, with their improved sensitivity, can potentially detect shorter timescale variability and further constrain the size of the VHE emission region.


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