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Observation of the galaxy M87 with VERITAS

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Abstract: The giant radio galaxy M87 is the only extragalactic non-blazar object which has been detected as a source of very high energy γ-rays. It represents a unique opportunity to study the phenomena of γ-ray emission from a nearby AGN. In this paper we report preliminary results from the observations of M87 taken with the imaging atmospheric Cherenkov telescope array VERITAS in February, March and April 2007. An excess of photons above an energy threshold of 250 GeV is measured with a statistical significance of more than five standard deviations.

Introduction

M87 is a nearby giant elliptical galaxy ($\sim$16 Mpc) which lies near the center of the Virgo galaxy cluster. It is a powerful radio source (Virgo A), classified as a Fanaroff-Riley class I (FR I) radio galaxy [1]. Its core is an AGN powered by a supermassive black hole of about 3.2×10^9 $M_\odot$ [2], emitting the first-detected plasma jet [3] which extends over several kiloparsecs. According to the unified scheme [4] of BL Lacertae objects (BL Lac) and FR I radio galaxies, M87 should be of the same astrophysical nature as BL Lac but with its jet not pointing along the line of sight. The critical sight angle between BL Lac and FR I galaxies is not well known. Some models propose an M87 jet misalignement around 30° [5] but superluminal motion observed by HST [6] in the M87 jet suggest an orientation within 19° of the line of sight. The TeV emission from M87 establishes an important link between M87 and BL Lac objects, which may have implications for the unified scheme, since all other extragalactic sources detected in the TeV regime are BL Lac objects [7].

M87 has been observed over a broad range of energies from radio waves to γ-rays. Its jet is resolved in radio, optical and X-ray regimes and shows similar morphologies at all wavelengths. This emission is understood as the synchrotron radiation from high energy electrons in the jet. The same electron population could also be responsible for the TeV γ-ray emission through the inverse Compton process [8]. Models involving protons [9] can also explain the TeV emission.

In fact, M87 is also considered as a possible source of ultra-high-energy ($\sim$$10^{20}$ eV) cosmic rays [10]. As tracers of high-energy hadrons, very-high-energy γ-rays could provide important clues to help determine the origin of extragalactic cosmic rays.

The first detection of M87 in the TeV regime was reported by the HEGRA collaboration [11] with a statistical significance of 4.1 standard deviations. This was confirmed by the HESS collaboration [12] which also reported rapid variability and an unexpectedly hard spectrum. The imaging atmospheric Cherenkov technique provides insufficient angular resolution ($\sim$ 3 arcmin) to resolve the M87 emitting region (core, jet...) but the day scale variability measured by HESS suggesting a very small region, most likely close to the core. The observation of superliminal motion of extremely compact radio structures within the HST-1 region has however recently provided indications the TeV emission could originate from that region, 0.82" (60 pc projected) from the core [13].

Observation with VERITAS

VERITAS is an array of four imaging atmospheric Cherenkov telescopes with 12 m-diameter mirror and 3.5° field of view camera. Telescopes details can be found in these proceedings [14]. The array is located in southern Arizona where M87 reaches more than 70° in elevation.

The observations in the direction of M87 were carried out during 51 hours from February to April 2007 at elevations from 55° to 71°. All data were taken in "Wobble" mode, tracking M87 with a 0.5° offset (successively north, south, east, west). VERITAS was still under construction and most of the observations were performed with a partial array of three telescopes. In order to check the source variability, we processed all the data in the same way, using only the first three telescopes even when the fourth telescope was in use (6% of the data set). We selected usable data on the basis of the weather conditions and the raw trigger rate stability. About 90% of the data pass our quality selection cuts (cf. Table 1).

Data Analysis

The data have been analyzed using independent analysis packages (see [15] for details on the analysis). All of these analysis yield consistent results. The presented results are obtained with the GrISU package [16]. This analysis chain differs from those described in [15] by fixed thresholds in the image cleaning (same thresholds for all pixels) and by the background-rejection cuts. In this analysis, the background-rejection cuts were optimized for the detection of a point-like source with a luminosity of 10% of the Crab Nebula. The signal from the source ("ON") is the number of events with a reconstructed direction less than 0.14° from the source direction. The backround rate ("OFF") is estimated using seven "mirror" regions which have the same area and the same distance from the camera center (0.5°) as the "ON" region (reflected region method [15]). The statistical significance is calculated using the Li and Ma formula [17] (with $\alpha = 1/7$).

This analysis, applied to the Crab Nebula data taken with the 3-telescope-array configuration at

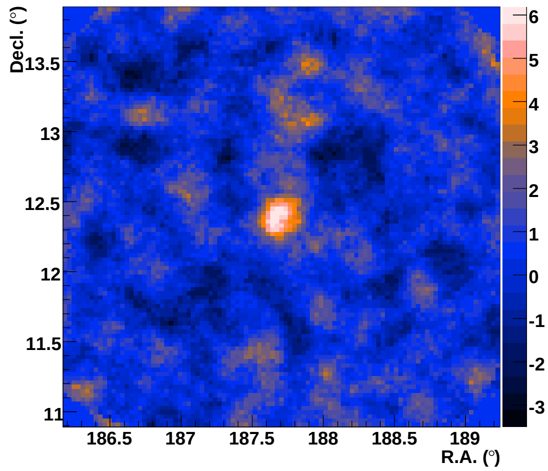

Figure 1: Excess significance map of the M87 surrounding region.

$\sim$78° elevation in February 2007, results in an excess of 5.9 γ/min for a background rate of 0.75 $\mathrm{evt/min}$ (Li & Ma excess significance of 27.5 $\sigma/\sqrt{\mathrm{h}}$). In this preliminary paper, we express the measured γ-ray flux in Crab units. Simulations and data show the excess rate does not vary significantly ($< 10\%$) between 78° and the M87 observation elevation.

Preliminary results

VERITAS detected an excess of 263 events from the direction of M87, corresponding to a statistical significance of 5.1 standard deviations (secondary analysis yield also a significance above 5 standard deviations). The energy threshold of our analysis at the M87 observation elevation has been estimated with Monte Carlo simulations at 250 GeV. The time averaged excess rate corresponds to a γ-ray flux of 1.7% of the Crab nebula flux.

Figure 1 shows the map of the excess significance in the surrounding region of M87. The excess position is: R.A. $12^h\ 30^m\ 47.5^s \pm 11^s$, Dec. $+12°23'23'' \pm 1'48''$, consistent with the position of M87 (R.A. $12^h\ 30^m\ 49.4^s$, Dec. +12° 23' 28"). Figure 2 shows the distribution of the square of the angle θ between M87 and the reconstructed direc-

Date	Observation time		Results	
	raw	selected	excess rate	significance
12-25 Febr.	17.0 h	15.5 h	0.14 ± 0.04 /min	$4.2\ \sigma$
12-20 March	23.5 h	20.4 h	0.07 ± 0.03 /min	$2.6\ \sigma$
07-19 April	10.7 h	8.3 h	0.10 ± 0.05 /min	$2.2\ \sigma$
TOTAL	51.2 h	44.2 h	0.10 ± 0.02 /min	$5.1\ \sigma$

Table 1: Data set toward M87 taken with VERITAS in spring 2007

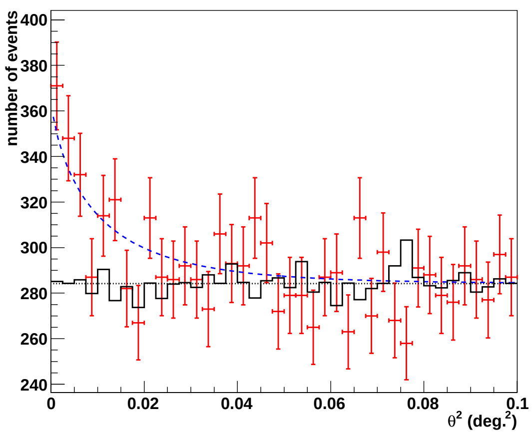

Figure 2: Crosses show the θ^2 distribution from M87 and the solid line from off-source directions. The dashed line is the θ^2 distribution expected for a point-like source with a backround level represented by the dotted line.

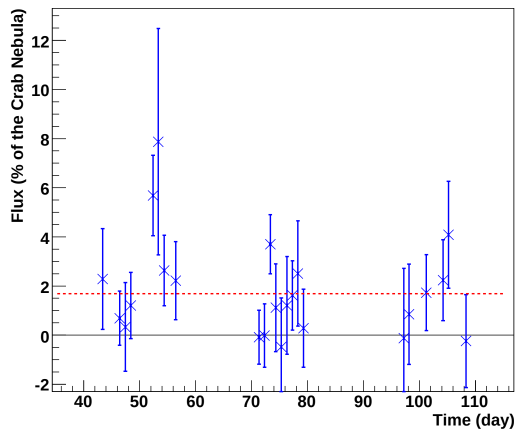

Figure 3: Nightly average (crosses) and global average (dashed line) of the M87 γ-ray flux above 250 GeV as a function of the observation day of year.

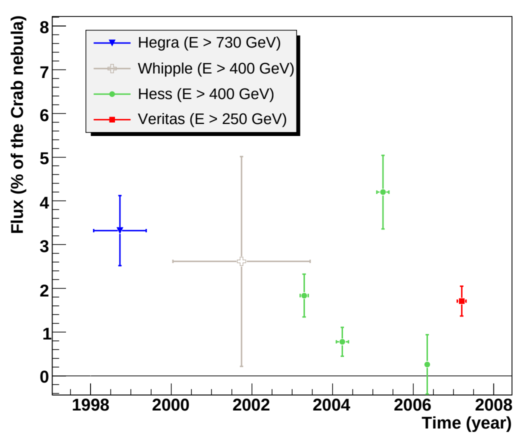

Figure 4: M87 flux reported by very high energy γ-ray telescopes as a function of observation year.

tion. The shape of the excess is compatible with a point-like source (dashed line). The upper limit to the source extension has a 2.3 arcmin radius.

Figure 3 shows the M87 light curve night-by-night during the three months of observation. No significant variability is observed. The constant flux fit χ^2 per free parameters is: 21.4/22. The maximal deviation of the rate from the average (February 21 and 22) reaches only 3.4 standard deviations. We cannot yet confirm the variability on a 2-day scale reported by the HESS collaboration.

Figure 4 shows the M87 flux recorded during the last 10 years by HEGRA [11], Whipple 10 m [18], HESS [12] and VERITAS expressed in Crab units. The 2007 flux reported in this paper is at an average level.

Summary and Conclusion

VERITAS confirms the γ-ray emission from M87 above 250 GeV. The measured flux is below 2% of the Crab Nebula flux, comparable to earlier observations with HESS and HEGRA. This result demonstrates the capability of VERITAS for detecting a faint source in 50h of observations.

Acknowledgements

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