

Observation of gamma-ray emission from the galaxy M 87 above 250 GeV with VERITAS

V.A. Acciari¹, M. Beilicke², G. Blaylock³, S.M. Bradbury⁴, J.H. Buckley², V. Bugaev², Y. Butt⁵, O. Celik⁶, A. Cesarini⁷, L. Ciupik⁸, P. Cogan⁹, P. Colin^{*10}, W. Cui¹¹, M.K. Daniel⁴, C. Duke¹², T. Ergin³, A.D. Falcone¹³, S.J. Fegan⁶, J.P. Finley¹¹, G. Finnegan¹⁰, P. Fortin¹⁴, L.F. Fortson⁸, K. Gibbs⁵, G.H. Gillanders⁷, J. Grube⁴, R. Guenette⁹, G. Gyuk⁸, D. Hanna⁹, E. Hays^{15 16 17}, J. Holder¹⁸, D. Horan¹⁶, S.B. Hughes², M.C. Hui¹, T.B. Humensky¹⁵, A. Imran¹⁹, P. Kaaret²⁰, M. Kertzman²¹, D.B. Kieda¹⁰, J. Kildea⁵, A. Konopelko¹¹, H. Krawczynski², F. Krennrich¹⁹, M.J. Lang⁷, S. LeBohec¹⁰, K. Lee², G. Maier⁹, A. McCann⁹, M. McCutcheon⁹, J. Millis¹¹, P. Moriarty¹, R. Mukherjee¹⁴, T. Nagai¹⁹, R.A. Ong⁶, D. Pandel²⁰, J.S. Perkins⁵, M. Pohl¹⁹, J. Quinn²², K. Ragan⁹, P.T. Reynolds²³, H.J. Rose⁴, M. Schroedter¹⁹, G.H. Sembroski¹¹, A.W. Smith⁴, D. Steele⁸, S.P. Swordy¹⁵, A. Syson⁴, J.A. Toner⁷, L. Valcarcel⁹, V.V. Vassiliev⁶, S.P. Wakely¹⁵, J.E. Ward²², T.C. Weekes⁵, A. Weinstein⁶, R.J. White⁴, D.A. Williams²⁴, S.A. Wissel¹⁵, M.D. Wood⁶, B. Zitzer¹¹.

ABSTRACT

The multiwavelength observation of the nearby radio galaxy M 87 provides a unique opportunity to study in detail processes occurring in Active Galactic Nuclei from radio waves to TeV γ -rays. Here we report the detection of γ -ray emission above 250 GeV from M 87 in spring 2007 with the VERITAS atmospheric Cherenkov telescope array and discuss its correlation with the X-ray emission. The γ -ray emission is measured to be point-like with an intrinsic source radius less than 4.5 arcmin. The differential energy spectrum is fitted well by a power-law function: $d\Phi/dE = (7.4 \pm 1.3_{stat} \pm 1.5_{sys}) \times (E/\text{TeV})^{(-2.31 \pm 0.17_{stat} \pm 0.2_{sys})} 10^{-9} \text{m}^{-2} \text{s}^{-1} \text{TeV}^{-1}$. We show strong evidence for a year-scale correlation between the γ -ray flux reported by TeV experiments and the X-ray emission measured by the ASM/RXTE observatory, and discuss the possible short-time-scale variability. These results imply that the γ -ray emission from M 87 is more likely associated with the core of the galaxy than with other bright X-ray features in the jet.

Subject headings: Galaxy: individual(M 87, Virgo A, NGC 4486) - gamma rays: observation - VERITAS

*Corresponding author: colin@physics.utah.edu

¹Department of Life and Physical Sciences, Galway-Mayo Institute of Technology, Galway, Ireland

²Department of Physics, Washington University, St. Louis, MO 63130, USA

³Department of Physics, University of Massachusetts, Amherst, MA 01003, USA

⁴School of Physics and Astronomy, University of Leeds, Leeds, LS2 9JT, UK

⁵Fred Lawrence Whipple Observatory, Harvard-Smithsonian Center for Astrophysics, Amado, AZ 85645, USA

⁶Department of Physics and Astronomy, University of

California, Los Angeles, CA 90095, USA

⁷Physics Department, National University of Ireland, Galway, Ireland

⁸Astronomy Department, Adler Planetarium and Astronomy Museum, Chicago, IL 60605, USA

⁹Physics Department, McGill University, Montreal, QC H3A 2T8, Canada

¹⁰Department of Physics, University of Utah, Salt Lake City, UT 84112, USA

¹¹Department of Physics, Purdue University, West Lafayette, IN 47907, USA

¹²Department of Physics, Grinnell College, Grinnell, IA 50112-1690, USA

¹³Department of Astronomy and Astrophysics, Pennsylv-

1. Introduction

The giant elliptical galaxy M 87 is a nearby (~ 16 Mpc) powerful FR I (Fanaroff & Riley 1974) radio galaxy (Virgo A) which lies near the center of the Virgo cluster. Its core is an Active Galactic Nucleus (AGN) powered by a supermassive black hole of $(3.2 \pm 0.9) \times 10^9 M_{\odot}$ (Macchetto et al. 1997), emitting the first-observed plasma jet (Curtis 1918). M 87 has been observed over a broad range of energies from radio waves to TeV γ -rays. Its jet is resolved in radio, optical and X-ray regimes and shows similar morphologies at all these wavelengths. M 87 is the first non-blazar AGN observed to emit TeV γ -rays and it provides valuable insight into the acceleration of high-energy particles in astrophysical jets.

The first detection of M 87 in the TeV regime was reported by the HEGRA collaboration (Aharonian et al. 2003) with a statistical significance of 4.1 standard deviations derived from observations made during 1998-99. This detection was confirmed by the HESS collaboration (Aharonian et al. 2006A), which also reported a year-scale flux variability and strong indications of rapid variability (2-day scale) during a high state of γ -ray activity in 2005. The imaging atmospheric Cherenkov technique

provides insufficient angular resolution (few arcminutes) to resolve the M 87 emission region, but the day-scale variability claimed by HESS suggests a very small region, most likely close to the core. The confirmation of such short-time-scale variability is of paramount importance because of its implications regarding the source dimensions.

The rapid variability of M 87 γ -ray emission would also constitute an important connection with the most common extragalactic sources detected in the TeV regime. These are all generally considered to be BL Lacertae (BL Lac) objects with the jet pointing towards the observer (blazar). The TeV emission of M 87 is now generally interpreted in the frame of the unified scheme of AGN (Urry & Padovani 1995). According to this scheme, FR I radio galaxies are of the same nature as BL Lac objects, but with their jet not pointing along the line of sight. Typical models assume a M 87 jet misalignment around 30° - 35° (Bicknell & Begelman 1996). However, superluminal motion has been observed in the compact first knot, HST-1, in the optical (Biretta et al. 1999) and radio domains (Cheung et al. 2007). To explain this requires a jet orientation closer to the line of sight (within 19°) at least at this location in the jet. The HST-1 emission also shows “blazar-like” behavior with very strong month-scale variability in the radio, optical and X-ray wavelengths (Harris et al. 2007), much stronger than the variability observed in the nucleus or in the other knots.

The non-thermal emission of the jet is understood as synchrotron radiation from high-energy electrons, and the TeV γ -rays could result from inverse-Compton scattering by the same electron population. A time correlation between the X-ray synchrotron radiation and the TeV emission is then expected. Models explain the TeV emission as originating from electrons either in the inner jet close to the core and the jet emission base (TeV blazar-type model) (Georganopoulos et al. (2005), Ghisellini et al. (2005), Lenain et al. (2007), Tavecchio & Ghisellini (2008)), or in the large-scale jet (Stawarz et al. (2003), Honda & Honda (2007)). On intermediate scale, it was recently proposed the TeV emission comes from the peculiar knot HST-1 (Stawarz et al. 2006). Since the year-scale variability is established, the core region and the knot

vania State University, PA 16802, USA

¹⁴Department of Physics and Astronomy, Barnard College, Columbia University, NY 10027, USA

¹⁵Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA

¹⁶Argonne National Laboratory, Argonne, IL 60439, USA

¹⁷now at N.A.S.A./Goddard Space-Flight Center, Greenbelt, MD 20771, USA

¹⁸Department of Physics and Astronomy and the Bartol Research Institute, University of Delaware, Newark, DE 19716, USA

¹⁹Department of Physics and Astronomy, Iowa State University, Ames, IA 50011, USA

²⁰Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242, USA

²¹Department of Physics and Astronomy, DePauw University, Greencastle, IN 46135-0037, USA

²²School of Physics, University College Dublin, Belfield, Dublin 4, Ireland

²³Department of Applied Physics and Instrumentation, Cork Institute of Technology, Bishopstown, Cork, Ireland

²⁴Santa Cruz Institute for Particle Physics and Department of Physics, University of California, Santa Cruz, CA 95064, USA

HST-1 are more likely the source of the TeV emission than the large-scale jet.

The origin of the TeV emission could also not be in the jet but in the vicinity of the central supermassive black hole of M 87. The rotating magnetosphere of the black hole could accelerate particles (pulsar-type model) producing electromagnetic cascades and then TeV γ -rays by inverse-Compton scattering (Neronov & Aharonian (2007), Rieger & Aharonian (2008)). This model could explain a day-scale variability of the TeV emission.

An alternative model involving protons has also been proposed (Reimer et al. 2004). In this model, the TeV γ -ray emission is dominated by neutral pion production, and by proton and muon synchrotron radiation in the highly magnetized environment of the jet formation region (Synchrotron-Proton-Blazar model). In this context, M 87 would be an efficient cosmic rays accelerator. It was even suggested that M 87 is the source of most ultra-high-energy cosmic rays detected on Earth (Biermann et al. 2001). However the SPB model predicts a quite soft spectrum in the TeV range, softer than what was recently measured by HESS and VERITAS.

Another model, involving dark matter annihilation, has also predicted TeV γ -ray emission from M 87 (Baltz et al. 2000). But the variability of the flux almost excludes this scenario as the main contributor to the TeV emission. Dark matter is expected to be distributed over much larger distance scales than those implied by the recently established year-scale variability.

Studies of the variability time scale and of coincident multiwavelength observations are very important for discriminating between these models.

2. Observations and analysis

The Very Energetic Radiation Imaging Telescope Array System (VERITAS) is a γ -ray observatory located in southern Arizona. It is an array of four 12 m-diameter imaging atmospheric Cherenkov telescopes, each with a 499-pixel photomultiplier-tube camera covering a 3.5° field of view (Holder et al. 2006). The energy range covered extends from 100 GeV (zenith observation) up to tens of TeV.

The observations of M 87 were carried out over 51 hours between February to April 2007 at eleva-

tions from 55° to 71° . In spring 2007, VERITAS was still in its construction phase. The M 87 observations were performed with an array of either three telescopes (94% of the data) or four telescopes (6%). The performance of the array during this period is discussed elsewhere (Maier et al. 2007). In order to minimize systematic errors on the estimation of the flux and its variability, we do not use the data from the fourth telescope, which was not fully calibrated at this time. We processed all the data in the same way, using only three telescopes, even when data from the fourth telescope were available.

Only good-quality data were considered for the analysis. Our data selection is based on weather conditions and raw trigger rate stability. About 90% of the data (44 h) pass our quality selection cuts. The selected data have been processed with several independent analysis packages (Daniel et al. 2007). The results presented here come from one of these packages and the others yield consistent results. The analysis chain uses two-threshold image cleaning, stereo reconstruction and cosmic-ray rejection based on standard image parameter cuts (Hillas 1985). The energy of each shower is reconstructed using a method based on the quantity of light measured by the telescopes and on the position of the shower-core ground impact. The differential energy spectrum is unfolded using the correction-factor method described in Chapter 11 of “Statistical Data Analysis” (Cowan 1998).

All observations were taken in “wobble” mode, tracking M 87 with a 0.5° offset north, south, east or west from the camera center. In this mode the cosmic-ray background rate is estimated using several “mirror” regions at the same distance from the camera center (0.5°) as the nominal source position. We compare the number of events with the reconstructed shower direction in these off-source regions (seven in this analysis) to the number of events in a region centred on the nominal source position. The radius of each region is 0.13° . Statistical significances are calculated using the Li and Ma formula (equation 17 in Li & Ma (1983)).

3. VERITAS results

We detected an excess of 259 ± 44 events from the direction of M 87, corresponding to a statis-

tical significance of 5.9 standard deviations. The analysis energy threshold for the average elevation of the M87 observations (66°) is approximately 250 GeV, estimated from Monte Carlo simulations. The time-averaged excess rate ($0.10 \pm 0.02 \gamma/\text{min}$) corresponds to 1.9% of the Crab Nebula rate observed at similar elevations.

Figure 1 shows the map of the excess significance in the sky region of M87. The detected source (VER J1230+123) is consistent with a point-like source located inside the M87 galaxy. The position of the maximum of a 2D Gaussian fit of the excess is: R.A. $12^h 30^m 46^s \pm 4^s_{stat} \pm 6^s_{sys}$, Decl. $+12^\circ 23' 21'' \pm 50''_{stat} \pm 1'30''_{sys}$, compatible with the position of the M87 core (R.A. $12^h 30^m 49.4^s$, Decl. $+12^\circ 23' 28''$). Figure 2 shows the distribution of the square of the angle θ between M87 and the reconstructed shower direction. The shape of the excess is compatible with a point-like source (dashed line). The upper limit (99%) of the intrinsic source extension has a $4.5'$ radius.

The differential energy spectrum has been measured from 250 GeV to 8 TeV. Table 1 gives the differential flux and statistical error at different energies. In order to keep the reconstructed energy bias below 10%, the flux of the lowest energy bin (250 GeV) has been estimated using only data taken at elevation above 62° (34.8 h of observation). The M87 spectrum obtained is consistent with a power-law spectrum: $d\Phi/dE = \Phi_0 \cdot (E/\text{TeV})^\Gamma$ with a flux normalization constant $\Phi_0 = (7.4 \pm 1.3_{stat} \pm 1.5_{sys}) 10^{-9} \text{m}^{-2} \text{s}^{-1} \text{TeV}^{-1}$ and a spectral index $\Gamma = -2.31 \pm 0.17_{stat} \pm 0.2_{sys}$. The $\chi^2/\text{d.o.f.}$ of the fit is 3.0/4. Figure 3 shows this spectrum and its power-law fit and compares them with the previous spectra measured by HESS in 2004 and 2005 (Aharonian et al. 2006A). Data points from a recent re-analysis of the HEGRA data (Götting 2006) are also shown. The results of this HEGRA re-analysis will be used hereafter.

Correlation between the spectral index and the flux have been observed in BL lac objects such as Mrk 501 (Djannati et al. 1999) and Mrk 421 (Krennrich et al. (2002), Albert et al. (2007)). Unfortunately, the γ -ray flux from M87 being so close to the sensitivity of the present generation of atmospheric Cherenkov telescopes, the uncertainties on the spectral index do not permit to make any statement on a possible similar behavior.

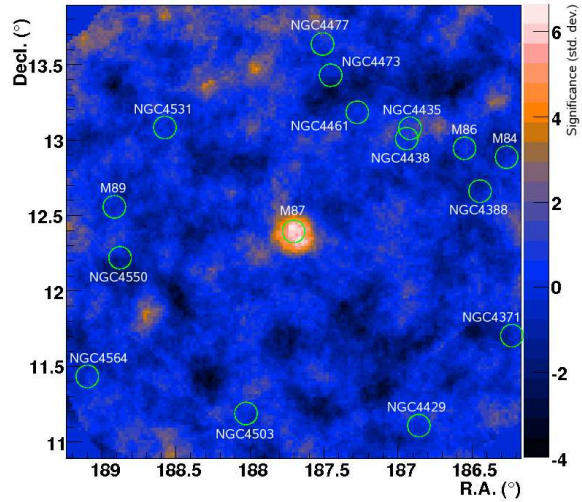


Fig. 1.— Significance map of the region surrounding M87 measured with VERITAS (in units of standard deviation). Circles show the positions of the brightest galaxies of the Virgo cluster.

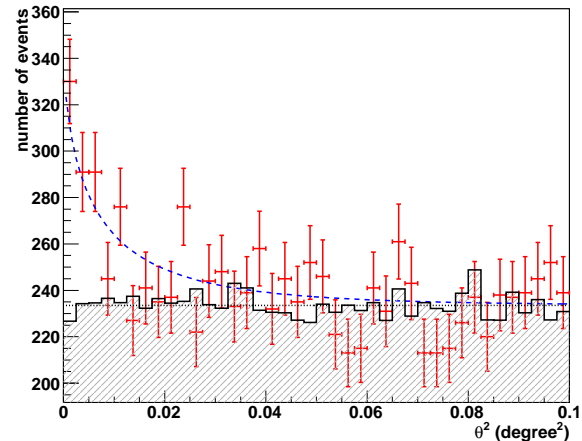


Fig. 2.— The data points with error bars show the θ^2 distribution from M87 and the solid histogram that from off-source directions. The dashed line is the θ^2 distribution expected for a point-like source with a background level represented by the dotted line.

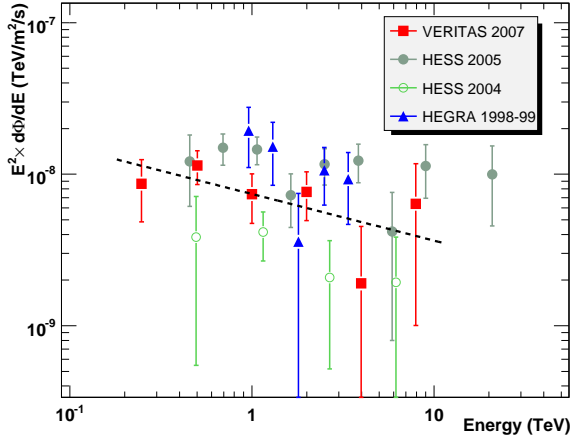


Fig. 3.— Spectral energy distribution of M87 measured with VERITAS in 2007 and with other experiments during the previous years. The dashed line shows the power-law fit of the VERITAS data (see text).

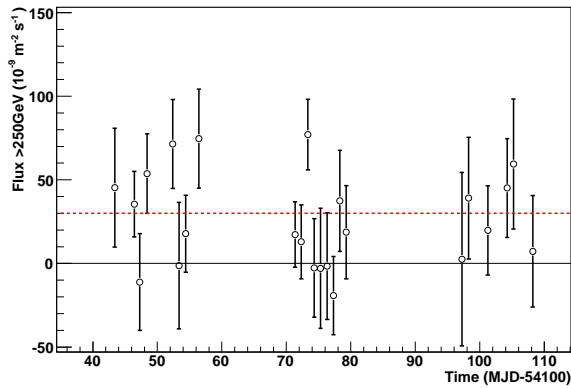


Fig. 4.— Nightly average (circles) and global average (dashed line) of the M87 γ -ray flux above 250 GeV measured with VERITAS as a function of the day of year 2007.

The γ -ray flux shows significant variability from one year to another. The first panel of Figure 5 shows the integral γ -ray flux reported by the HEGRA, HESS and VERITAS collaborations. For ease of comparison, the VERITAS flux was scaled to the energy threshold of 730 GeV commonly used by HEGRA and HESS. The integral flux above 730 GeV is estimated according to our spectral analysis result (power-law spectrum with a spectral index $\Gamma=-2.31$):

$$\Phi_{>730\text{GeV}} = (8.5 \pm 1.5_{\text{stat}} \pm 1.7_{\text{sys}}) 10^{-9} \text{m}^{-2} \text{s}^{-1}.$$

The TeV γ -ray lightcurve consists of data points from different experiments. The preliminary result for the Crab Nebula, standard candle of the TeV astronomy, observed with VERITAS in spring 2007 (Celik et al. 2007) is in good agreement with the flux reported by HEGRA (Aharonian et al. 2004) and HESS (Aharonian et al. 2006B). Thus, the differences observed with different detectors comes from real variations of the M87 flux.

Figure 4 shows the M87 γ -ray flux night-by-night during the three months of observation with VERITAS. No significant short-time-scale variability is observed. The constant flux fit χ^2 per degree of freedom (d.o.f.) is 24.3/22. The maximum deviation from the average (MJD 54173) is only 2.2 standard deviations.

4. X-ray / γ -ray correlation

The All-Sky Monitor (ASM) on the Rossi X-ray Timing Explorer (RXTE) has been monitoring the M87 emission between 2 keV and 10 keV since early 1996 (Levine et al. 1996). Measurements are performed with sequences of 90-second "dwells". The light-curve data used here are the quick-look

Table 1: Differential flux of M87 measured with VERITAS in spring 2007

Energy (TeV)	Differential flux ($\text{m}^{-2} \text{s}^{-1} \text{TeV}^{-1}$)	Significance (std dev.)
0.25	$(1.36 \pm 0.60) 10^{-7}$	2.26
0.50	$(4.55 \pm 1.15) 10^{-8}$	3.97
1.00	$(7.39 \pm 2.65) 10^{-9}$	2.80
2.00	$(1.92 \pm 0.68) 10^{-9}$	2.82
3.98	$(1.20 \pm 1.66) 10^{-10}$	0.73
7.94	$(1.01 \pm 0.85) 10^{-10}$	1.19

results provided by the ASM/RXTE team on their web site¹, dwell-by-dwell and as a daily average.

In order to check the long-term variability of the ASM/RXTE signal, we sum the data by bins of 6 months using the standard practice of weighting measurements by $1/\sigma^2$, where σ is the measurement uncertainty. The second panel of Figure 5 shows the average ASM/RXTE rate for the first six months of each year (i.e. the period coinciding with the observation of M87 with the ground-based detectors) since 1996. The ASM/RXTE lightcurve has similar variations as the TeV lightcurve shown in the first panel. Figure 6 shows the γ -ray flux, $\Phi_{>730\text{GeV}}$, plotted versus the ASM/RXTE rate, X_{rate} . Taking the error bars, which correspond to the statistical error, into account, the linear correlation coefficient is 0.78 ± 0.11 (positive correlation confidence level $> 99.99\%$). The most recent analysis of the HEGRA data has been used to calculate this correlation coefficient.

A marginal correlation between the TeV γ -ray and the ASM/RXTE rate was previously suggested by the Whipple 10 m-telescope collaboration in 2000-01 (LeBohec et al. 2003A) and was discussed in the doctoral theses of M. Beilicke (2006) and of N. Götting (2006). Such a correlation between the TeV and hard X-ray emissions has been also detected in the BL lac objects Mrk 501 (Djannati et al. (1999), Krawczynski et al. (2002)) and Mrk 421 (Fossati et al. 2007). The correlation for these two objects is generally close to quadratic but depends on the energy range considered (Katarzynski et al. 2005).

We estimate the value of both the variable and the steady components of the X-ray emission of M87 by fitting the TeV correlation plot with a linear relation:

$$\Phi_{>730\text{GeV}} = (88 \pm 23) \cdot (X_{rate} - (1.196 \pm 0.022)) \cdot 10^{-9}$$

and with a quadratic relation:

$$\Phi_{>730\text{GeV}} = (338 \pm 180) \cdot (X_{rate} - (1.142 \pm 0.042))^2 \cdot 10^{-9}.$$

In these two equations $\Phi_{>730\text{GeV}}$ is expressed in $\text{m}^{-2}\text{s}^{-1}$ and X_{rate} in count/s . Both functions fit the data well with a $\chi^2/\text{d.o.f.} < 1$. They show that the X-ray emission consists of both a dominant steady emission (1.1-1.2 count/s) and a variable fraction ($< 20\%$) strongly correlated with the γ -ray emission.

The constant part of the X-ray emission is dominated by the thermal emission from the $\sim 2\text{keV}$ gaseous atmosphere of the M87 galactic halo (Forman et al. 2007). The variable part could result from synchrotron emission by high-energy particles with cooling time less than one year. The emission site for the variable component must have a compact size on the order of one lightyear or less ($\sim 5\text{mas}$ at the M87 distance), or be moving at relativistic speed in a direction close to the line of sight, to explain the yearly variability recorded.

The only known M87 regions which have such characteristics are the core and the brightest knots of the jet. The *Chandra* X-ray observatory has been used to monitor the M87 jet emission in the 0.2-6 keV energy range since 2000 (Harris et al. 2006) with enough angular resolution to measure separately the flux from the different features. Figure 5 shows the light curves of the two dominant X-ray features which are the core and HST-1. Since 2003, HST-1 has been flaring and it largely dominates the *Chandra* X-ray flux. However the variation of the flux from this knot does not seem to correlate well with the variation of the ASM/RXTE signal. Between 2003 and 2005 the HST-1 X-ray emission increased by a factor of 20 whereas the variable fraction of the ASM/RXTE rate changed by less than a factor of two. The same goes for the new flux measurement with VERITAS which clearly do not follow the X-ray lightcurve of HST-1.

The next-brightest features of the jet observed with *Chandra* can explain only with difficulty the ASM/RXTE rate variation as their fluxes are significantly weaker than the HST-1 X-ray variation. Actually, the energy range of ASM/RXTE (2-10 keV) is higher than that of *Chandra* (0.2-6 keV) and the dominant features of the ASM/RXTE energy band may not be HST-1. According to the spectral analysis of *Chandra* data taken in 2000 (Perlmutter & Wilson 2005), the core was the only bright X-ray feature with a harder spectrum than HST-1. Thus the core seems the best candidate to dominate HST-1 in hard X-rays and provide substantial ASM/RXTE rate variation. Moreover the confidence level for a positive linear correlation between the 6-month average rates of ASM/RXTE and *Chandra* is higher for the core (90%) than for HST-1 (65%). Since the variable component of the ASM/RXTE flux is likely dominated by X-ray

¹<http://xte.mit.edu/asmlc/ASM.html>

emission from the core, and there is a strong correlation between the TeV and ASM/RXTE fluxes, we conclude that the core is the most likely candidate for the source of the TeV γ -ray emission.

It is however surprising that the large HST-1 flare in 2005 does not show in AMS/RXTE as this implies a very soft HST-1 spectrum. There is no evidence for such a soft spectrum in the *Chandra* data. Unfortunately, during the flaring period of HST-1, spectral analysis of the core and HST-1 seems impossible because the flux was so strong that the bulk of the events in the image are piled, and this destroys the spectral information. Furthermore the core is separated by only $0.86''$ from HST-1, and its *Chandra* signal can be contaminated by the HST-1 signal. As shown in Harris et al. (2007), the small flare of the core in 2005 can be almost smoothed out by subtracting 5% of the HST-1 signal (dotted line in the third panel of the figure 5). This is probably indicative of the uncertainties on the core flux measurement with *Chandra* during this period.

Motivated by the long-time-scale correlation between X_{rate} and $\Phi_{>730\text{GeV}}$, we searched for a similar correlation on a 5-day scale. Such short-time-scale correlation had previously been suggested from earlier Whipple 10m data (LeBohec et al. 2003B). This study was also designed to improve our sensitivity to short-time-scale variations such as those reported by the HESS collaboration. Again, we express the VERITAS results as the integral γ -ray flux above 730 GeV. Figure 7 shows $\Phi_{>730\text{GeV}}$ versus X_{rate} summed on contiguous and independent 5-day-scale bins. The confidence level for a positive correlation is only 82%. The statistics are too poor for us to draw any conclusion as to a possible extension of the year-scale correlation (dash-dotted line) to the 5-day scale. Simultaneous observations of M 87 with VERITAS and ASM/RXTE will continue in the coming years, providing the opportunity to investigate further such short-time-scale correlation.

5. Conclusion

The VERITAS collaboration observed M 87 in spring 2007 with an array of three telescopes. The analysis of the 44 hours of data provides a 5.9 standard deviation detection of γ -ray emission above 250 GeV. The energy spectrum is fitted well

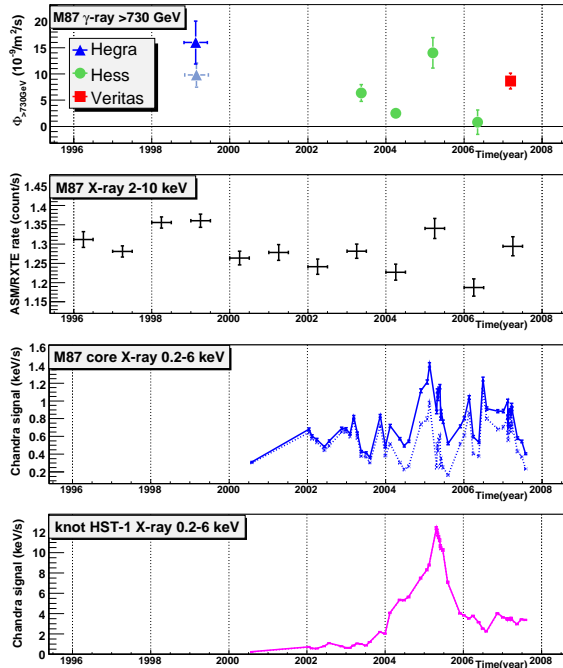


Fig. 5.— The first panel shows the integral γ -ray flux above 730 GeV reported by the HEGRA, HESS and VERITAS collaborations. Concerning the HEGRA flux, both the published result (light color) and the most recent re-analysis result (dark color) are shown (see text for references). The second panel shows the January-to-June average of the global X-ray emission of M 87 measured with ASM/RXTE in the range 2-10 keV. The last two panels show the M 87 core and the knot HST-1 X-ray emission measured with *Chandra* in the range 0.2-6 keV. The dotted line on the third panel shows the corrected core signal from which 5% of the HST-1 signal were subtracted (Harris 2007).

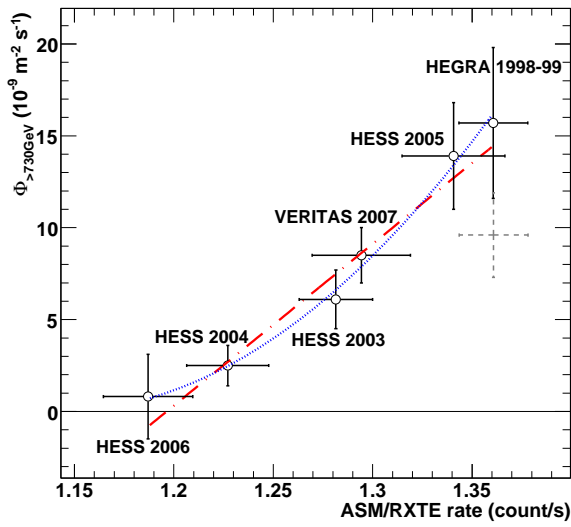


Fig. 6.— Correlation between M87 emission in X-ray (ASM/RXTE data: 2-10 keV) and in γ -ray (HEGRA, HESS, VERITAS data: >730 GeV). The dash-dotted line is the linear correlation fit and the dotted line shows the quadratic correlation fit. For HEGRA, both the published flux (dashed lines) and the reanalysis result (solid lines) are shown.

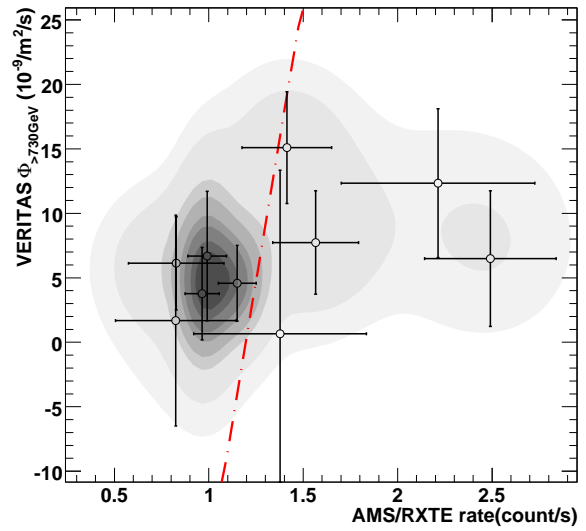


Fig. 7.— M87 X-ray emission (ASM/RXTE data: 2-10 keV) plotted relative to the very-high-energy γ -ray emission (VERITAS data: >730 GeV) for contemporaneous observations. Data are binned in a 5-day intervals. The dash-dotted line shows the linear correlation fit obtained for the year-scale correlation in figure 6. The grey contours are the sum of 2D Gaussian functions associated with each data point according to its uncertainty.

by a power-law function: $d\Phi/dE = (7.4 \pm 1.3_{stat} \pm 1.5_{sys}) \times (E/\text{TeV})^{(-2.31 \pm 0.17_{stat} \pm 0.2_{sys})} 10^{-9} \text{m}^{-2} \text{s}^{-1} \text{TeV}^{-1}$.

The comparison of our result with the spectra reported by the HESS and the HEGRA collaborations does not indicate a variability of the spectral index.

In most TeV γ -ray emission models, a correlation between the γ -ray and X-ray flux is expected and the relationship can be used to distinguish between models. We have found strong evidence for such a correlation from M87. We have shown a year-scale correlation between the γ -ray flux above 730 GeV, recorded by imaging atmospheric Cherenkov telescopes during the last ten years, and the X-ray flux in the energy range 2-10 keV recorded with ASM/RXTE. Both linear and quadratic functions fit this correlation well. The poor correlation between the ASM/RXTE rate variations and the dominant X-ray features (HST-1) observed by *Chandra* in the 0.2-6 keV energy band is surprising but, in the light of the correlation with the TeV flux, it suggests HST-1 is unlikely to be the main source of the γ -ray emission. If the core indeed has a harder spectrum than HST-1, it could dominate in the ASM/RXTE energy range, and be the most likely site of the detected TeV emission. HESS observations of M87 in 2005 were suggestive of a 2-day-scale variability. The VERITAS observations in 2007 showed it to be in a lower state and, even with a short-time-scale X-ray correlation study, the statistics of this observation are insufficient to confirm such rapid variability. Further observations and multiwavelength campaigns on M87 at a range of activity states will prove important in tracking down the site of the high-energy emission, determining the particle acceleration mechanism and the relation to the blazar class of high-energy objects.

The authors are grateful to the ASM/RXTE teams at MIT and at the RXTE SOF and GOF at NASA's GSFC and specially to Ron Remillard who provided the ASM/RXTE data. We also thank Dan Harris for his comments on the *Chandra* observations.

VERITAS is supported by grants from the U.S. Department of Energy, the U.S. National Science Foundation and the Smithsonian Institution, by NSERC in Canada, by PPARC in the U.K. and by Science Foundation Ireland.

Facilities: VERITAS, HEGRA, HESS, RXTE (ASM), CXO (ACIS).

REFERENCES

- Aharonian F. et al. (HEGRA coll.) 2003, *A&A*, 403, L1
- Aharonian F. et al. (HEGRA coll.) 2004, *ApJ*, 614, 897
- Aharonian F. et al. (HESS coll.) 2006A, *Science*, 314, 1424
- Aharonian F. et al. (HESS coll.) 2006B, *A&A*, 457, 899
- Albert et al (MAGIC coll.) 2007, *ApJ*, 663 125
- Baltz, E. A. et al. 2000, *Phys. Rev. D*61, 023514
- Beilicke, M. 2006, thesis on Dissertation.de ISBN 3-86624-112-7
- Bicknell, G. V. & Begelman, M. C. 1996, *ApJ*, 467, 597
- Biermann. et al. 2001, *Physics and astrophysics of UltraHigh-Energy Cosmic Rays*, M. Lemoine & G. Sigl (Berlin: springer).
- Biretta, J.A., Sparks, W. B. & Macchetto, F. 1999, *ApJ*, 520, 621
- Celik, O. et al. (VERITAS coll.) 2007, in Proc. 30th ICRC, Mérida, Mexico, 1209
- Cheung, C. C., Harris, D. E. & Stawarz, L. 2007, *ApJ*, 663, L65
- Cowan, G. 1998, *“Statistical Data Analysis”*, Oxford University Press
- Curtis, H. D. 1918, *Publ. Lick Obs.*, 13, 9
- Daniel, M. K. et al. (VERITAS coll.) 2007, in Proc. 30th ICRC, Mérida, Mexico, 283
- Djannati-Ataï A. et al. (CAT coll.) 1999, *A&A*, 350, 17
- Fanaroff, B. L. & Riley, J. M. 1974, *MNRAS*, 167, 31P
- Forman, W. et al. 2007, *ApJ*, 665, 1057
- Fossati, G. et al. 2007, accepted by *ApJ*, arXiv:0710.4138

- Georganopoulos, M., Perlman, E. S. & Kazanas D. 2005, ApJ, 634, L33
- Ghisellini, G., Tavecchio, F. & Chiaberge, M. 2005, A&A, 432, 401
- Götting, N. 2006, thesis on Dissertation.de ISBN 3-86624-243-2
- Harris, D. E. et al. 2006, ApJ, 640, 211
- Harris, D. E. et al. 2007, arXiv:0707.3124
- Harris, D. E. 2007, private communication.
- Hillas, M. 1985, in Proc. 19th ICRC, La Jolla, USA, 3, 445
- Holder, J. et al. (VERITAS coll.) 2006, Astropart. Phys. 25, 391
- Honda, M. & Honda, Y. S. 2007, ApJ, 654, 885
- Katarzynski, K. et al. 2005, A&A 433, 479
- Krawczynski, H., Coppi, P. S. 2002, & Aharonian, F. A. MNRAS, 337, 721
- Krennrich, F. et al. (Whipple 10m coll.) 2002, ApJ, 575, L9
- Le Bohec, S. et al. (Whipple 10m coll.) 2003A, ApJ, 610, 156
- Le Bohec, S. et al. (Whipple 10m coll.) 2003B, in Proc. 28th ICRC, Tsukuba, Japan
- Lenain, J.-P. et al. 2007, accepted by A&A, arXiv:0710.2847
- Levine, M. et al. 1996, ApJ, 469, L33
- Li, T. P. & Ma, Y. Q. 1983, ApJ, 272, 317
- Perlman, E. S. & Wilson, A. S. 2005, ApJ, 627, 140
- Macchetto, F. et al. 1997, ApJ, 489, 579
- Maier, G. et al. (VERITAS coll.) 2007, in Proc. 30th ICRC, Mérida, Mexico, 810
- Neronov, A. & Aharonian, F. A. 2007, ApJ, 671, 85
- Reimer, A., Protheroe, R. J. & Donea, A.-C. 2004, A&A, 419, 89
- Rieger, F. M. & Aharonian, F. A. 2008, accepted by A&A, arXiv:0712.2902
- Stawarz, L., Sikora, M. & Ostrowski, M. 2003, ApJ, 597, 186
- Stawarz, L. et al. 2006, MNRAS, 370, 981
- Tavecchio, F. & Ghisellini, G. 2008, accepted by MNRAS, arXiv:0801.0593
- Urry, C. M. & Padovani, P., PASP, 107, 803