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OBSERVATION OF M87 AT 400 GeV WITH THE WHIPPLE 10 METER TELESCOPE

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ABSTRACT

We present results from observations taken with the Whipple 10 m very high energy γ-ray telescope with maximal sensitivity at 400 GeV during 39 hr between 2000 and 2003 in the direction of the giant radio galaxy M87. Using the entire data set, we derive a 99% confidence level upper limit on the flux of γ-ray emission above 400 GeV from M87 to be $\leq 6.9 \times 10^{-12}$ cm^{-2} s^{-1}. This suggests variability at the 90% confidence level when compared to the flux measured by the HEGRA collaboration in 1999 if the differential spectrum is steeper than a power law of index 3.75. Our search for a correlation between the *Rossi X-Ray Timing Explorer* all-sky monitor observation and a potential γ-ray signal is inconclusive.

Subject headings: galaxies: active — galaxies: individual (M87) — gamma rays: observations

1. INTRODUCTION

M87 is a nearby ($D \simeq 16$ Mpc) giant elliptical radio galaxy (Virgo-A) showing a one-sided jet, and thus it has been classified as a Fanaroff-Riley Class I (FR-I) object. The kiloparsec jet, the first ever observed (Curtis 1918), is most likely powered by a supermassive ($M \sim 3 \times 10^9\ M_\odot$) black hole (Harms et al. 1994) located at the center of the galaxy. The jet emission extends from the radio to optical (Marshall et al. 2002) and X-ray regimes. The proximity of M87 makes it possible to resolve structures in all three domains. The similar morphology of the jet at all three wavelength regimes suggests that they are of common origin.

The nonthermal emission is almost certainly synchrotron radiation, as indicated by several observational facts. The polarization in the radio and optical emission (Baade 1956; Fraix-Burnet et al. 1989; Owen et al. 1989) is naturally explained by the synchrotron mechanism. Furthermore, the X-ray spectrum is steeper than the radio spectrum, supporting the synchrotron origin of the X-ray emission (Reynolds et al. 1999). *Chandra* X-ray observations revealed strongly variable radiation from the core and base of the jet (Harris et al. 2003), which concurs well with a synchrotron picture. On the basis of these observations, the presence of 10 TeV electrons in the jet have been deduced by various authors (Harris & Krawczynski 2002; Biretta 1991).

Most active galaxies detected in very high energy (VHE) γ-rays ($E > 100$ GeV) have their jet axes closely aligned with the observer's line of sight; hence, they are blazars. To date, the following six TeV blazars that have been firmly established: Mrk 421 (Punch et al. 1992), 1ES 1959+650 (Nishiyama et al. 1999; Holder et al. 2003; Aharonian et al. 2003), PKS 2155−304 (Chadwick et al. 1999; Djannati-Ataï et al. 2003), Mrk 501 (Quinn et al. 1996), H1426+428 (Horan et al. 2002; Aharonian et al. 2002; Djannati-Ataï et al. 2002), and 1ES 2344+514 (Catanese et al. 1998; Tluczykont et al. 2003).

All these TeV blazars are classified as high-frequency peaked BL Lac objects (HBLs) showing a luminosity peak at X-rays energies with some of them (1ES 2344+514, H1426+428, and Mrk 501) reaching the hard X-ray regime. This is in contrast to most γ-ray blazars detected at GeV energies by EGRET (Hartman et al. 1999), which are generally

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TABLE 1
Epochs and Durations of M87 On-Source Observations with the Whipple 10 m Telescope

Date	ON-OFF (28 minute runs)	TRACK (28 minute runs)
2000 Jan–Apr	6	13
2001 Jan–Apr	8	7
2002 Jan–Feb	12	3
2003 Jan–May	33	1

low-frequency peaked BL Lac objects (LBLs). The origin of the high-energy γ-rays is still an open question since both leptonic and hadronic models can be used to interpret the observations.

Within the context of unification models, it is possible to consider M87 a misaligned BL Lac object (Tsvetanov et al. 1998) seen at an angle of $\sim 30°$ (Bicknell & Begelman 1996) with superluminal motion observed at the base of the jet (Biretta 1995). It is not clear whether M87 should be regarded as a misaligned HBL or LBL (Perlman et al. 2001a; Protheroe et al. 2003), the latter being less favorable to the possibility of high-energy γ-ray emission. Modeling M87 as a misaligned HBL, Bai & Lee (2001) predict a detectable γ-ray flux using the synchrotron self-Compton (SSC) model. A radio galaxy similar to M87, Cen A, has been detected (Grindlay et al. 1975) at 300 GeV at the 4 σ level. Bai & Lee (2001) also predict a detectable flux level for Cen A for existing imaging atmospheric Cerenkov telescopes.

A very high energy γ-ray emission could also result from the interactions of hadronic particles in the jet. For example, the synchrotron-proton blazar (SPB) model was used by Protheroe et al. (2003) to make predictions about the γ-ray flux from M87. The SPB model provides a natural link to the production of ultrahigh-energy cosmic rays. It was suggested that most ultrahigh-energy cosmic rays could come from M87 after having been deflected by the galactic wind (Biermann et al. 2001).

The SSC and the SPB models both suggest γ-ray flux variability at TeV energies similar to variability observed in X-rays. However, there are alternative scenarios in which γ-rays are produced over larger scales in M87. For example, the kiloparsec scale could produce high-energy γ-rays through inverse Compton scattering of ambient photons (Stawarz et al. 2003). Interaction of hadronic cosmic rays with the interstellar medium of M87 could also produce detectable levels of high-energy γ-rays via neutral pion decay (Pfrommer & Ensslin 2003). Another mechanism for γ-ray emission from M87 is the annihilation of supersymmetric dark matter (Baltz et al. 2000). Hence, due to the large differences in size of the emission region for the latter models, variability of γ-ray emission from M87 could become an important criterion for distinguishing them from models tied to the base of the jet. In any case, the detection of very high energy γ-rays from M87 would open up a new class of nearby active galactic nuclei with a range of physics topics to be explored.

M87 has been observed by the HEGRA and Whipple collaborations. Both groups originally reported upper limits (Götting et al. 2001; Le Bohec et al. 2001). The HEGRA collaboration, after applying a more sensitive analysis method, recently reported a 4 σ detection based on 83.4 hr of observation with a flux of $(0.96 \pm 0.23) \times 10^{-12}$ cm^{-2} s^{-1} above 730 GeV (Aharonian et al. 2003). The HEGRA observations were carried out in 1999. The original Whipple 10 m upper limit came from observations in 2000 and 2001. We continued observing M87 in 2002 and 2003, and we present our entire data set (39 hr of observation) in this paper. After describing the data obtained toward M87 with the Whipple 10 m telescope, we present our search for a continuous signal and an X-ray–correlated signal. In § 5 we discuss the implications of our upper limits.

2. OBSERVATION WITH THE WHIPPLE 10 m TELESCOPE

Since 2000, the Whipple 10 m telescope has been used in an ongoing search for γ-ray emission from M87. The telescope is located at an altitude of 2300 m and consists of a 10 m diameter optical reflector with a fast photomultiplier tube camera in the focal plane. It records, in 20 ns exposures, the Cerenkov image of atmospheric showers produced by very high energy cosmic rays and by putative γ-ray photons originating from a cosmic source (Fegan 1997). The observations presented here were obtained using a camera covering a full field of view of $2\overset{\circ}{.}4$ with 379 photomultipliers in a close-packed hexagonal array with a $0\overset{\circ}{.}12$ center-to-center spacing (Finley et al. 2001). The source was observed under good conditions for a total of 2324 minutes (almost 39 hr) in 83 runs of 28 minutes duration, while at an elevation between 56° and 71°.

Most observations (a total of 1652 minutes on-source) were carried out in a standard ON-OFF mode in which the source (ON) is tracked for 28 minutes, after which the telescope tracks a background region (OFF) covering the same path in elevation and azimuth for another 28 minutes. The rest of the observations were carried out in a standard TRACK mode in which on-source observations are not complemented by a specific background observation. Each of the TRACK runs was later associated with an unrelated OFF run, obtained in the same period of time and at a similar elevation. Each TRACK run and its assigned background run were then processed in the same way as the standard ON-OFF data (de la Calle Perez 2003). Table 1 indicates the periods of time during which M87 observations were made with the Whipple 10 m telescope for each mode.

Software "padding" (Cawley 1993) is used to compensate for differences in noise levels in the ON and OFF runs. The image is also "cleaned" to alleviate the noise effects of pixels not part of the shower image. The image is then characterized by the image parameters (Hillas et al. 1985) calculated from the first and second moments of the recorded light distribution. The image parameters are length, width, and distance from the center of the field of view (Fegan 1997). In the standard analysis, at least 10 photoelectrons (30 digital counts) are required in each of the two brightest pixels of each image to ensure that the image is well above background noise. Boundary values for the length ($0\overset{\circ}{.}13$–$0\overset{\circ}{.}25$), width ($0\overset{\circ}{.}05$–$0\overset{\circ}{.}12$), and distance ($0\overset{\circ}{.}4$–$1\overset{\circ}{.}0$) parameters were derived by maximizing the significance of the Crab Nebula observations obtained with this camera. Images of γ-ray showers point back to the direction of origin, and in order to delineate potential signals, we define the image orientation angle α between 0° and 90° as the angle formed by the image major axis and the direction defined by the image centroid and the observed source position in the field of view. The signal is then expected to accumulate at values of α less than 15°. Let the number of events with $\alpha < 15°$ be $S_{\rm ON}$ and $S_{\rm OFF}$ and the number of events with $30° < \alpha < 90°$ be $B_{\rm ON}$ and $B_{\rm OFF}$, respectively, for the ON

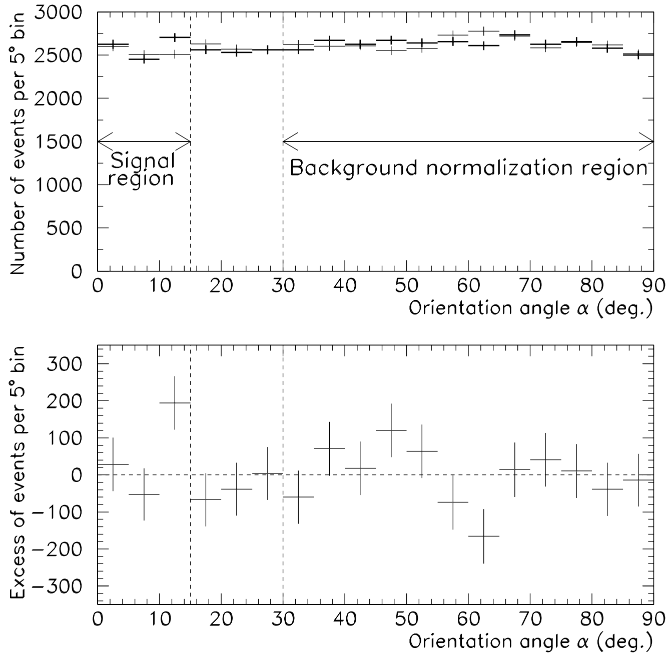

FIG. 1.—Distribution of the orientation angle for events satisfying the γ-ray selection criteria (*top*) for the ON (*thick line*) and OFF (*thin line*) data and the difference (*bottom*). The signal is expected in the range 0°–15°. For the data taken in TRACK mode, the OFF data were renormalized to match the ON statistic in the range 30°–90°.

and OFF data. For our ON-OFF data, a potential signal excess N and its statistical uncertainty δN were calculated according to (1)

$$N = S_{\rm ON} - S_{\rm OFF}, \quad (1)$$

$$\delta N = \sqrt{S_{\rm ON} + S_{\rm OFF}}.$$

For our TRACK mode data, we use the α angle distribution in the range 30°–90° to renormalize the background event rate from the a posteriori identified OFF-source data to the ON-source data. We estimate the event excess N and its statistical uncertainty (Bradbury et al. 1997) using (2)

$$N = S_{\rm ON} - (S_{\rm OFF} B_{\rm ON})/B_{\rm OFF}, \quad (2)$$

$$\delta N = \sqrt{S_{\rm ON} + \frac{S_{\rm OFF}^2 B_{\rm ON}^2}{B_{\rm OFF}^2}\left(\frac{1}{S_{\rm OFF}} + \frac{1}{B_{\rm ON}} + \frac{1}{B_{\rm OFF}}\right)}.$$

For well-matched data, the difference in background event rate between the ON-source and the OFF-source is not significant, but this rescaling has been applied systematically to the entire set of TRACK mode data.

3. SEARCH FOR A CONTINUOUS SIGNAL

When the standard analysis is applied to our 2000 and 2001 data (Le Bohec et al. 2001) with matched OFF data as described above, it yields a positive excess with a significance of 2.4 σ. This was in fact a motivation for continuing our M87 observing campaign in 2002 and 2003. The distribution of the α angle for γ-ray–like selected events in our entire data set obtained between 2000 and 2003 (see Table 1) is presented in Figure 1. There is no significant excess, and we derive the 99% confidence level upper limit on the γ-ray event rate to be 0.19 minute^{-1}. In order to convert rates to fluxes, we used the γ-ray event rate recorded from the Crab Nebula. To rescale the Crab Nebula spectrum, we used the spectral parameterization from Hillas et al. (1998), $(3.2 \pm 0.17 \pm 0.6) \times 10^{-11} \times (E/1\ {\rm TeV})^{-2.49 \pm 0.06_{\rm stat} \pm 0.04_{\rm syst}}$ cm^{-2} TeV^{-1} s^{-1}. The γ-ray event rate from the Crab slowly decreased after 2000. This results from the degradation of telescope efficiency. Since most of our M87 observations were done in 2003, and in order to be conservative in our upper limit estimations, we chose to use the Crab rate as measured in the 2002–2003 observing season, during 336 minutes under similar conditions as for the M87 observations. With the same analysis, we found the Crab rate to be 2.35 ± 0.15 minute^{-1}. From this, we derive the 99% confidence level upper limit on the γ-ray flux above 400 GeV from M87 to be $\leq 6.9 \times 10^{-12}$ cm^{-2} s^{-1} or ~8% of the Crab Nebula.

In order to calculate the flux over a range of energies, we have varied the software threshold by changing the required amount of light for the two brightest pixels of the image. The γ-ray–like event rate derived in each case is presented in Table 2 together with the energy of the peak response to a Crab Nebula–like spectrum. No significant excess was found, and we derived flux upper limits for each peak response energy. Using detailed simulations of the shower development and detector response, we verified that our upper limits depend on the spectral index (1.9–3.75) by less than 10. This results from expressing the integral flux in each case at the energy of the peak response to a Crab Nebula–like spectrum. With the standard analysis, the Whipple 10 m telescope provides sensitivity from ~250 GeV up to several tens of TeV with a maximum response to a typical power-law spectrum around 400 GeV. For steeper spectrum, the loss above 400 GeV is compensated by a gain below 400 GeV. In Figure 2, we compare our results to the flux by the HEGRA collaboration (Aharonian et al. 2003). There is no conflict between our upper limit and the HEGRA flux measurement at 730 GeV.

However, an extrapolation of the HEGRA result up to 1.6 TeV (3.2 TeV) with a power law of differential spectral

TABLE 2

ENERGY OF THE MAXIMAL RESPONSE TO A CRAB NEBULA–LIKE SPECTRUM AND RATES TOWARD THE CRAB NEBULA AND M87

$\max_1$, $\max_2$ (digital counts)	E (TeV)	Crab γ-Ray–like Event Rate (minute^{-1})	M87 γ-Ray–like Event Rate (minute^{-1})
30	0.4	2.35 ± 0.15	0.061 ± 0.056
70	0.8	1.450 ± 0.087	0.046 ± 0.024
140	1.6	0.500 ± 0.043	0.0063 ± 0.012
280	3.2	0.113 ± 0.020	0.0004 ± 0.0033

NOTE.—Rates toward the Crab Nebula and M87 for each peak response energy on the two strongest pixels in the image.

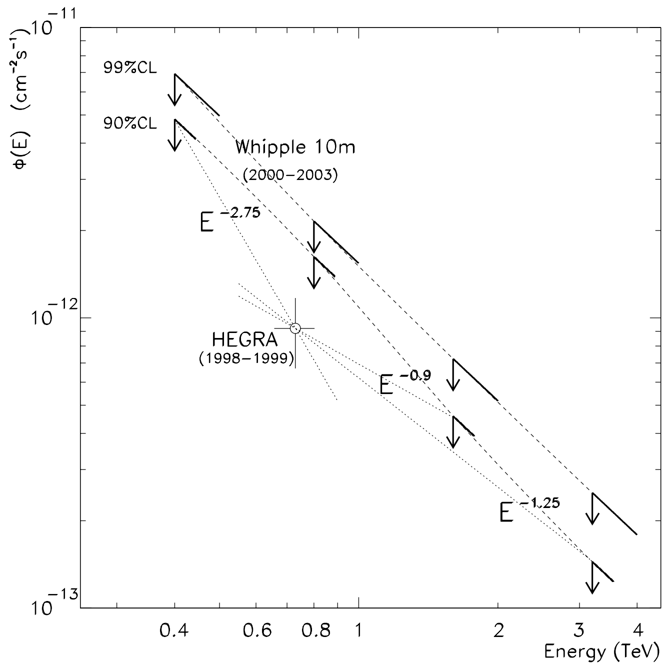

FIG. 2.—Whipple 10 m telescope upper limits on the integral γ-ray flux from M87. The dark lines with arrows indicate 99% and 90% confidence level upper limits for the standard analysis and various thresholds as indicated in Table 2. The slope of the dark lines indicates the slope of the Crab nebula integral spectrum that was used in deriving the upper limit. The dashed lines are power-law interpolations between the upper limits at different energy thresholds. The dotted lines are power laws connecting the HEGRA detection point (Aharonian et al. 2003) to the 90% confidence level upper limits to exhibit constraints on the energy spectrum hardness under the assumption of nonvariability. Unless the source is variable, a differential power-law spectrum of index smaller than 2.25 (1.9) up to 3.2 TeV (1.6 TeV) is excluded at the 90% level. A differential power-law spectrum of index larger than 3.75 down to 0.4 TeV is also excluded at the 90% level.

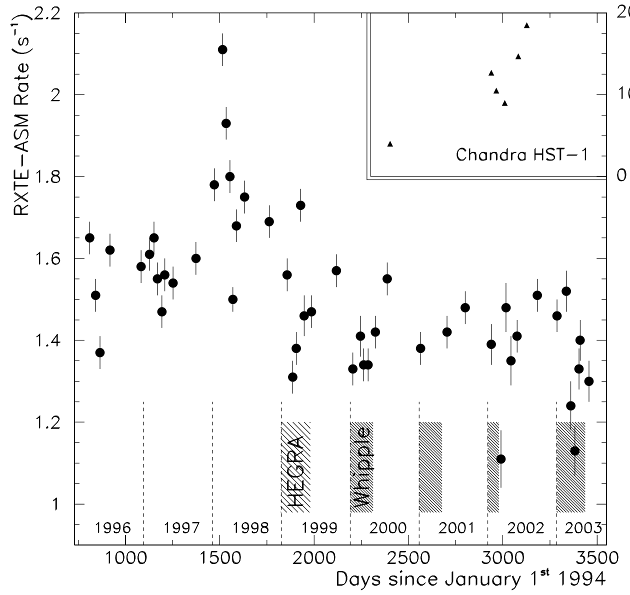

FIG. 3.—X-ray rate recorded with the *RXTE* ASM, which has been decreasing since 1996 (see http://xte.mit.edu). The HEGRA observation campaign directed at M87 in 1999 (*dashed box*) followed in 10 months by a fast-rising flare in 1998 extending over the following year. The Whipple 10 m telescope observing periods are indicated by the tightly dashed boxes. The box in the top right corner shows the HST-1 X ray flux recorded since 2000 with *Chandra* (Harris et al. 2003) on the same timescale.

index 1.9 (2.25) or harder is excluded at the 90% level. Assuming that the source is not variable, the differential energy spectrum of M87 would have to be softer than a power law of index 1.9 (2.25). On the other hand, an extrapolation of the HEGRA flux down to 400 GeV using a power law of differential spectral index 3.75 or softer is also excluded at the 90% level unless the source is variable. The range of differential spectral indices considered here is not excluded by the HEGRA measurement $\gamma = 2.9 \pm 0.8$ (Aharonian et al. 2003). Using a Monte Carlo calculation, we verified that connecting our 90% upper limits to the HEGRA flux measurement with power laws gives 90% confidence level limits on the actual spectral index.

4. SEARCH FOR A CORRELATION BETWEEN γ-RAY AND ALL-SKY MONITOR X-RAY RATES

In a search for possible correlations between TeV γ-rays and X-ray emission, we made a comparison between runs taken with the Whipple γ-ray telescope and the corresponding 1 day average rates recorded with the *RXTE* all-sky monitor (ASM).[19] The results of this study were promising in 2000 and 2001. The γ-ray excess we observed in 2000 and 2001 seems to result mostly from days for which the average ASM X-ray rates were the highest. The average ASM X-ray rate for our selected 2000–2001 data was found to be 1.24 s^{-1}. We searched for a γ-ray signal in runs taken on days for which the X-ray rate was smaller (16 runs) and larger (15 runs) than 1.24 s^{-1}. When M87 was in the low X-ray state we found a 0.6 σ excess, while we found a 3.0 σ excess when the source was in the higher X-ray state. However, the data we recorded in 2002 and 2003 did not confirm this tendency.

In 2002, *Chandra* recorded enhanced activity in M87 that reached levels higher by a factor $\sim$3 than those in 2000 (Harris et al. 2003; Perlman et al. 2003) in the jet and to a lesser extent in the core. If the 2000–2001 excess noticed in the Whipple 10 m data with some correlation with the X-ray activity were interpreted as a γ-ray signal, the absence of any excess in 2002–2003, a period of higher activity in M87, could be seen as resulting from absorption by the infrared radiation emitted by the heated low-temperature torus (Perlman et al. 2001b) in periods of higher activity, as proposed by Donea & Protheroe (2003) if the γ-rays are originating from the core. However, the X-ray flux increase observed with *Chandra* in 2002 is not large enough to be detected with the *RXTE* ASM because of its lower angular resolution. The *RXTE* ASM recorded a fast-rising flare at the beginning of 1998 (Fig. 3), just 10 months before the beginning of the HEGRA observation campaign. This would require the cooling time of the torus to be less than $\sim$10 months.

5. CONCLUSIONS

Observations of M87 at TeV energies carried out with the Whipple observatory 10 m telescope over the time period 2000–2003 do not show any significant γ-ray excess. From 39 hr of observations we derived a 99% confidence level upper limit on the flux of 6.9×10^{-12} cm^{-2} s^{-1} at energies larger than 400 GeV.

Our upper limits between 400 GeV and 3.2 TeV together with the HEGRA flux measurement constrain the energy spectrum of M87 under the assumption that the γ-ray flux is constant. The differential spectral index γ of M87 between

[19] The *RXTE* home page is available at http://xte.mit.edu.

400 GeV and 3.2 TeV is limited with 90% confidence to $2.25 < \gamma < 3.75$. The upper limit from EGRET observations of M87 of 0.4×10^{-7} cm^{-2} s^{-1} above 100 MeV (Sreekumar et al. 1994) indicates that assuming a power law between 100 MeV and 730 GeV, the differential spectral index cannot be larger than 2.2. Thus, the two spectral ranges have nominal overlap at a differential spectral index of $\sim$2.2. Since this is at the edge of both ranges, it indicates that the source is variable or cannot be described with a single spectral index.

In the framework of an SPB model, Protheroe et al. (2003) predict the differential energy spectrum of M87 could be even softer than a power law of index 3.75 with a strong sensitivity to the target photon spectrum (Reimer et al. 2004). Since the SPB model allows for time variability, this is consistent with our spectral constraints. Similarly, the SSC model, giving time-variable fluxes, is not constrained by these observations. In general, variability would be likely if the γ-ray radiation were produced in the core or at the base of the jet in M87, which shows variability at other wavelengths on timescales of less than 1 month (Tsvetanov et al. 1998).

On the other hand, γ-ray production models involving large scales, such as the kiloparsec jet, the interaction of cosmic rays with the interstellar medium in M87, and dark matter annihilation scenarios, naturally give a constant γ-ray flux. Hence, the spectral limits derived in this paper (a differential spectral index between 2.25 and 3.75) constrain these models. The emission model for the kiloparsec scale jet and the dark matter annihilation scenario are consistent with this constraint. The model based on cosmic rays interacting with the interstellar medium suggests a differential spectral index of less than 2.275 (Pfrommer & Ensslin 2003). This upper limit just barely overlaps with the range of spectral indices allowed by the analysis of observations given in this paper.

In order to discriminate large-scale emission scenarios from models involving the base of the jet, we have searched the data set for time variability. In fact, early observations of M87 in 2000–2001 show a 2.4 σ excess, whereas the significance of the total data set including the 2002–2003 observations was 1.1 σ. Neither result from the data subsets constitutes a detection. To enhance our sensitivity for possible time variations and flares, we have tried to correlate the γ-ray rate with X-ray data from the ASM. The underlying assumption is that M87 shows an X-ray/γ-ray connection as observed for TeV blazars. Although the 2000–2002 data looked promising, in that a correlation between X-ray and γ-ray fluxes were present, the entire 4 yr of observations do not support such a correlation.

If γ-ray variability were established for M87, this would exclude models involving the large-scale jet (Stawarz et al. 2003), the halo (Baltz et al. 2000), or the interstellar medium (Pfrommer & Ensslin 2003). Confirmation of the M87 very high energy γ-ray activity and possible variability now relies on the next generation of ground-based γ-ray observatories such as VERITAS, MAGIC, HESS, and CANGAROO, for which M87 should be a target of great interest.

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