

VERY HIGH ENERGY GAMMA-RAY OBSERVATIONS OF STRONG FLARING ACTIVITY IN M87
IN 2008 FEBRUARY

J. ALBERT,¹ E. ALIU,² H. ANDERHUB,³ L. A. ANTONELLI,⁴ P. ANTORANZ,⁵ M. BACKES,⁶ C. BAIXERAS,⁷ J. A. BARRIO,⁵
H. BARTKO,⁸ D. BASTIERI,⁹ J. K. BECKER,⁶ W. BEDNAREK,¹⁰ K. BERGER,¹ E. BERNARDINI,¹¹ C. BIGONGIARI,⁹ A. BILAND,³
R. K. BOCK,^{8,9} G. BONNOLI,¹² P. BORDAS,¹³ V. BOSCH-RAMON,¹³ T. BRETZ,¹ I. BRITVITCH,³ M. CAMARA,⁵ E. CARMONA,⁸
A. CHILINGARIAN,¹⁴ S. COMMICHAU,³ J. L. CONTRERAS,⁵ J. CORTINA,² M. T. COSTADO,^{15,16} S. COVINO,⁴ V. CURTEF,⁶ F. DAZZI,⁹
A. DE ANGELIS,¹⁷ E. DE CEA DEL POZO,¹⁸ R. DE LOS REYES,⁵ B. DE LOTTO,¹⁷ M. DE MARIA,¹⁷ F. DE SABATA,¹⁷
C. DELGADO MENDEZ,¹⁵ A. DOMINGUEZ,¹⁹ D. DORNER,¹ M. DORO,⁹ M. ERRANDO,² M. FAGIOLINI,¹² D. FERENC,²⁰
E. FERNÁNDEZ,² R. FIRPO,² M. V. FONSECA,⁵ L. FONT,⁷ N. GALANTE,⁸ R. J. GARCÍA LÓPEZ,^{15,16} M. GARCZARCZYK,⁸
M. GAUG,¹⁵ F. GOEBEL,⁸ M. HAYASHIDA,⁸ A. HERRERO,^{15,16} D. HÖHNE,¹ J. HOSE,⁸ C. C. HSU,⁸ S. HUBER,¹ T. JOGLER,⁸
D. KRANICH,³ A. LA BARBERA,⁴ A. LAILLE,²⁰ E. LEONARDO,¹² E. LINDFORS,²¹ S. LOMBARDI,⁹ F. LONGO,¹⁷ M. LÓPEZ,⁹
E. LORENZ,^{3,8} P. MAJUMDAR,⁸ G. MANEVA,²² N. MANKUZHYYIL,¹⁷ K. MANNHEIM,¹ L. MARASCHI,⁴ M. MARIOTTI,⁹
M. MARTÍNEZ,² D. MAZIN,^{2,29} M. MEUCCI,¹² M. MEYER,¹ J. M. MIRANDA,⁵ R. MIRZOYAN,⁸ S. MIZOBUCHI,⁸ M. MOLES,¹⁹
A. MORALEJO,² D. NIETO,⁵ K. NILSSON,²¹ J. NINKOVIC,⁸ N. OTTE,^{8,23,27} I. OYA,⁵ M. PANNIELLO,^{15,28} R. PAOLETTI,¹²
J. M. PAREDES,¹³ M. PASANEN,²¹ D. PASCOLI,⁹ F. PAUSS,³ R. G. PEGNA,¹² M. A. PEREZ-TORRES,¹⁹ M. PERSIC,^{17,24} L. PERUZZO,⁹
A. PICCIOLI,¹² F. PRADA,¹⁹ E. PRANDINI,⁹ N. PUCHADES,² A. RAYMERS,¹⁴ W. RHODE,⁶ M. RIBÓ,¹³ J. RICO,^{25,2} M. RISSI,³
A. ROBERT,⁷ S. RÜGAMER,¹ A. SAGGION,⁹ T. Y. SAITO,⁸ M. SALVATI,⁴ M. SANCHEZ-CONDE,¹⁹ P. SARTORI,⁹ K. SATALECKA,¹¹
V. SCALZOTTO,⁹ V. SCAPIN,¹⁷ T. SCHWEIZER,⁸ M. SHAYDUK,⁸ K. SHINOZAKI,⁸ S. N. SHORE,²⁶ N. SIDRO,²
A. SIERPOWSKA-BARTOSIK,¹⁸ A. SILLANPÄÄ,²¹ D. SOBCZYNSKA,¹⁰ F. SPANIER,¹ A. STAMERRA,¹² L. S. STARK,³ L. TAKALO,²¹
F. TAVECCHIO,⁴ P. TEMNIKOV,²² D. TESCARO,^{2,29} M. TESHIMA,⁸ M. TLUCZYKONT,¹¹ D. F. TORRES,^{25,18} N. TURINI,¹² H. VANKOV,²²
A. VENTURINI,⁹ V. VITALE,¹⁷ R. M. WAGNER,^{8,29} W. WITTEK,⁸ V. ZABALZA,¹³ F. ZANDANEL,¹⁹ R. ZANIN,² AND J. ZAPATERO⁷

Received 2008 May 30; accepted 2008 August 8; published 2008 August 22

ABSTRACT

M87 is the only known nonblazar radio galaxy to emit very high energy (VHE) gamma rays. During a monitoring program of M87, a rapid flare in VHE gamma-rays was detected by the MAGIC telescope in early 2008. The flux was found to be variable above 350 GeV on a timescale as short as 1 day at a significance level of 5.6σ . The highest measured flux reached 15% of the Crab Nebula flux. We observed several substantial changes of the flux level during the 13 day observing period. The flux at lower energies (150–350 GeV), instead, is compatible with being constant. The energy spectrum can be described by a power law with a photon index of $2.30 \pm 0.11_{\text{stat}} \pm 0.20_{\text{sys}}$. The observed day-scale flux variability at VHE prefers the M87 core as source of the emission and implies that either the emission region is very compact (just a few Schwarzschild radii) or the Doppler factor of the emitting blob is rather large in the case of a nonexpanding emission region.

Subject headings: galaxies: active — galaxies: individual (M87, NGC 4486) — gamma rays: observations

I. INTRODUCTION

M87 is a giant elliptical radio galaxy (RG) of Fanaroff Riley I type (FR I; Fanaroff & Riley 1974) in the Virgo Cluster at a distance of 16 Mpc (Macri et al. 1999). It is powered by a supermassive black hole (BH) of $(3.2 \pm 0.9) \times 10^9 M_{\odot}$ (Macchetto et al. 1997). The M87 jet was the first-ever observed (Curtis 1918), and due to the proximity of M87, its morphological substructures can be resolved and a unique view of its innermost regions is

possible. The jet, originating from the RG core, extends to $20''$ (Marshall et al. 2002; equivalent to a 2 kpc projected linear distance). Several compact regions (“knots”) along its axis are resolved in the radio, optical, and X-ray regimes. These knots have similar morphologies in all wave bands, although the X-ray knots appear to be tens of pc closer to the core than the optical and radio knots (Wilson & Yang 2002). The variable brightness of the knots may be due to several shock fronts in the jet, being responsible for particle acceleration and nonthermal emission. Su-

¹ Universität Würzburg, D-97074 Würzburg, Germany.

² IFAE, Edifici Cn., Campus UAB, E-08193 Bellaterra, Spain.

³ ETH Zurich, CH-8093 Zurich, Switzerland.

⁴ INFN National Institute for Astrophysics, I-00136 Rome, Italy.

⁵ Universidad Complutense, E-28040 Madrid, Spain.

⁶ Technische Universität Dortmund, D-44221 Dortmund, Germany.

⁷ Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain.

⁸ Max-Planck-Institut für Physik, D-80805 Munich, Germany.

⁹ Università di Padova and INFN, I-35131 Padova, Italy.

¹⁰ University of Łódź, PL-90236 Lodz, Poland.

¹¹ DESY, Deutsches Elektr.-Synchrotron, D-15738 Zeuthen, Germany.

¹² Università di Siena, and INFN Pisa, I-53100 Siena, Italy.

¹³ Universitat de Barcelona (ICC/IEEC), E-08028 Barcelona, Spain.

¹⁴ Yerevan Physics Institute, AM-375036 Yerevan, Armenia.

¹⁵ Inst. de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain.

¹⁶ Depto. de Astrofísica, Universidad, E-38206 La Laguna, Tenerife, Spain.

¹⁷ Università di Udine, and INFN Trieste, I-33100 Udine, Italy.

¹⁸ Institut de Ciències de l’Espai (IEEC-CSIC), E-08193 Bellaterra, Spain.

¹⁹ Inst. de Astrofísica de Andalucía (CSIC), E-18080 Granada, Spain.

²⁰ University of California, Davis, CA 95616-8677.

²¹ Tuorla Observatory, Turku University, FI-21500 Piikkiö, Finland.

²² Inst. for Nucl. Research and Nucl. Energy, BG-1784 Sofia, Bulgaria.

²³ Humboldt-Universität zu Berlin, D-12489 Berlin, Germany.

²⁴ INAF/Osservatorio Astronomico and INFN, I-34143 Trieste, Italy.

²⁵ ICREA, E-08010 Barcelona, Spain.

²⁶ Università di Pisa, and INFN Pisa, I-56126 Pisa, Italy.

²⁷ Current address: University of California, Santa Cruz, CA-95064.

²⁸ Deceased.

²⁹ Send offprint requests to D. Mazin, mazin@ifae.es; D. Tescaro, diegot@ifae.es; R. M. Wagner, rwagner@mppmu.mpg.de.

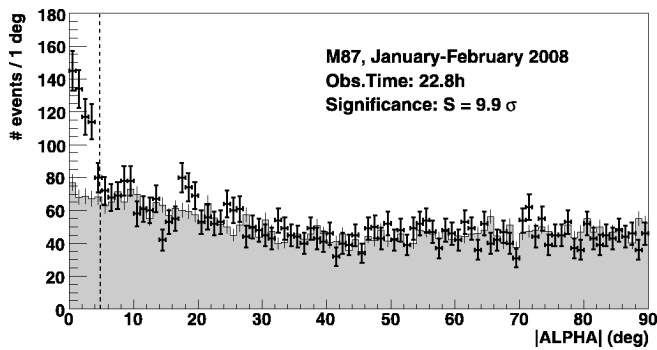


FIG. 1.— $|\text{ALPHA}|$ distribution for the overall data sample. The background (gray histogram) is estimated using three OFF regions arranged symmetrically to the ON-source region with respect to the camera center. A γ -ray excess with a significance of 9.9 standard deviations is obtained.

perluminal motion of the knots has been observed in the optical (Biretta 1996) and radio (Forman et al. 2007) wave bands, constraining the viewing angle of the jet to $<43^\circ \pm 4^\circ$.

The innermost resolved bright knot HST-1 is located at $0.82''$ (64 pc) from the core and is the most prominent feature of the jet. HST-1 has shown many flares exceeding the luminosity of the M87 core emission. Its X-ray brightness has increased by a factor >50 from 2000 to 2005 (Harris 2006). A correlation between radio, optical, and X-ray luminosity points to a common origin of the emission. The measured superluminal motion in HST-1 is higher than in other knots, suggesting a viewing angle of $<19^\circ$ for this part of the jet. The core itself is variable, too, and also shows a correlation between the emission levels from radio frequencies through X-rays (Perlman et al. 2003).

M87 was not detected by EGRET. The first hint of very high energy (VHE; >250 GeV) γ -ray emission was reported by Aharonian et al. (2003), and later confirmed by Aharonian et al. (2006) and Acciari et al. (2008). The emission is variable on a timescale of years. The reported ≈ 2 day variability (Aharonian et al. 2006) narrows down the size of the emission region to be on the order of the light-crossing time of the central BH. With its expected low accretion rate, the M87 core radiation is not strong enough to attenuate significantly TeV γ -rays even at 5 Schwarzschild radii (R_S) away from the BH (Neronov & Aharonian 2007). All this implies a production region in the immediate vicinity of the M87 core. During later observations, no significant flux variation was found (Acciari et al. 2008). An X-ray–VHE γ -ray correlation is expected in most emission models, but was not unambiguously found so far. Whereas Aharonian et al. (2006) claim a hint of a correlation between the soft (0.3–10 keV) X-rays at HST-1 and the VHE γ -rays, Acciari et al. (2008) find a year-by-year correlation between the 2–10 keV X-ray flux of the M87 core and the VHE γ -ray emission instead, but do not observe a correlation between the two energy bands on shorter timescales.

The radio to X-ray emission of the jet is due to nonthermal synchrotron radiation of relativistic electrons in the jet. The observed knots and flares in M87 point to a complicated morphology with several shock fronts producing these electrons. While all 23 currently known extragalactic VHE γ -ray emitters³⁰ are blazars, M87 is assumed to be a blazar not aligned to our line of sight (Tsvetanov et al. 1998). If the observed VHE emission from M87 is associated with the innermost part of its jet, then blazar emission models may hold. In blazars without prominent disk or broad-line features, the VHE emission is explained by inverse Compton pro-

cesses involving the synchrotron photons and their parent electron population (synchrotron self-Compton models; e.g., Maraschi et al. 1992). Alternatively, in hadronic models, interactions of a highly relativistic jet outflow with ambient matter (Dar & Laor 1997; Beall & Bednarek 1999), proton-induced cascades (Mannheim 1993), or synchrotron proton radiation (Mücke & Protheroe 2001; Aharonian 2000) may produce VHE γ -rays. In such a scenario, M87 might also account for parts of the observed ultra-high-energy cosmic rays (Protheroe et al. 2003). It should be noted that for M87 the location of the VHE emission is still uncertain. Specific emission models for high-energy processes close to the core (Georganopoulos et al. 2005; Ghisellini et al. 2005; Lenain et al. 2008; Tavecchio & Ghisellini 2008), in the large-scale jet (Stawarz et al. 2003; Honda & Honda 2007), or in the vicinity of a BH (Neronov & Aharonian 2007; Rieger & Aharonian 2008) have been developed.

The MAGIC collaboration performed monitoring observations of M87 starting from 2008 January, sharing the task with the VERITAS and H.E.S.S. experiments. Here we report on MAGIC results from a subset of these data, revealing a variability timescale of M87 of 1 day. The energy spectrum and light curves are discussed.

2. OBSERVATIONS AND DATA ANALYSIS

The MAGIC telescope is located on the Canary Island of La Palma (2200 m above sea level, $28^\circ 45'$ north, $17^\circ 54'$ west). MAGIC is a stand-alone imaging air Cerenkov telescope (IACT) with a 17 m diameter tessellated reflector dish. MAGIC has a low-energy threshold of 50–60 GeV (trigger threshold at small zenith angles). The accessible energy range extends up to tens of TeV with a typical energy resolution of 20%–30%, depending on the zenith angle and energy (Albert et al. 2008a).

The data set comprises observations from 2008 January 30 to 2008 February 11. These were performed in the wobble mode (Daum et al. 1997) for 26.7 hr. The zenith angle of the observations ranges from 16° to 35° . After removing runs with unusually low trigger rates, mostly caused by bad weather conditions, the effective observing time amounts to 22.8 hr.

The data were analyzed using the MAGIC standard calibration and analysis (Albert et al. 2008a). The analysis is based on image parameters (Hillas 1985; Tescaro et al. 2007) and the random forest (RF; Albert et al. 2008b) method, which are used to define the so-called hadronness of each event. The cut in hadronness for γ /hadron separation was optimized on a contemporaneous data set of the Crab Nebula. After this cut the distribution of the angle ALPHA, which is the angle between the main image axis and the line between center of gravity of the image and the source position in the camera, is used to determine the signal in the ON-source region. Three background (OFF) sky regions are chosen symmetrically to the ON-source region with respect to the camera center. The final cut $|\text{ALPHA}| < 5^\circ$ (Fig. 1) was also optimized on the Crab Nebula data to determine the number of excess events and the significance of the signal.

The energies of the γ -ray candidates were also estimated using the RF method. To derive a differential energy spectrum, we applied looser cuts than those in Figure 1 to retain a higher number of γ -ray candidates and to lower the effective analysis threshold down to 150 GeV. Looser cuts also reduce systematic uncertainties between data and Monte-Carlo events, which is important for the estimation of the effective collection areas. The derived spectrum was unfolded to correct for the effects of the limited energy resolution of the detector (Albert et al. 2007). Finally, the spectrum and the light curves were corrected

³⁰ See, e.g., <http://www.mppmu.mpg.de/~rwagner/sources/> for an up-to-date list.

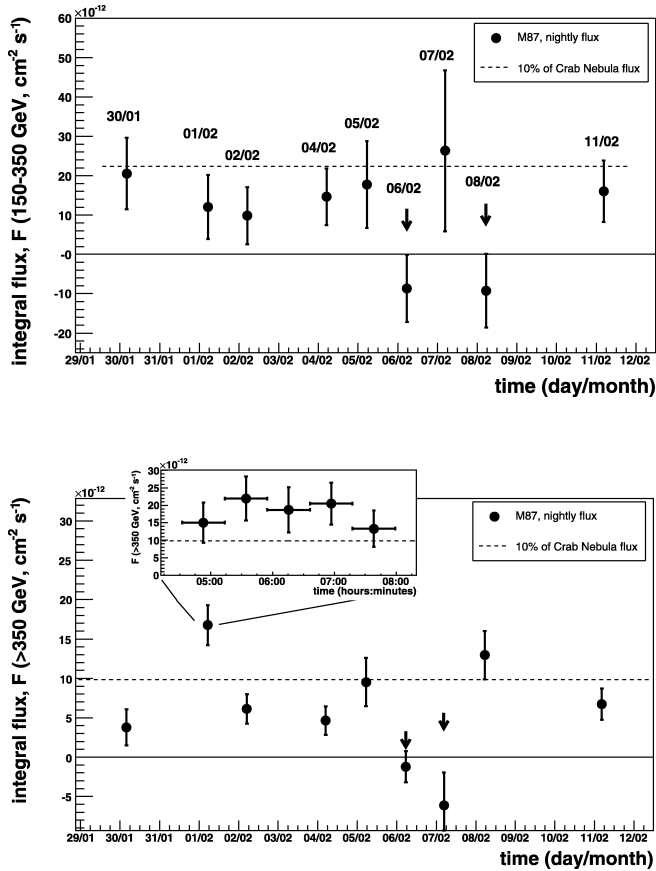


FIG. 2.—Night-by-night light curve for M87 as measured from 2008 January 30 (MJD 54,495) to 2008 February 11 (MJD 54,507). The top panel shows the flux in the energy bin 150–350 GeV, being consistent with a constant emission. The bottom panel shows the integral flux above 350 GeV; flux variations are apparent on variability timescales down to 1 day. The inset in the bottom panel shows the light curve above 350 GeV in a 40 minute time binning for the night with the highest flux (2008 February 1). The vertical arrows represent flux upper limits (95% c.l.) for the nights with negative excesses.

for trigger inefficiencies due to higher discriminator thresholds during partial moon light and twilight conditions (Albert et al. 2008c). These corrections are on the order of 0%–20%. The data were also analyzed with an independent analysis yielding, within statistical errors, the same results.

3. RESULTS

The $|\text{ALPHA}|$ distribution after so-called tight cuts is shown in Figure 1. The applied cuts are $\text{SIZE} > 450$ photoelectrons and hadronness $h < 0.02$. After the final $|\text{ALPHA}|$ cut (resulting in an overall cut efficiency of 37%), the total signal of 241 events over 349 normalized background events corresponds to an excess with a significance of 9.9σ along equation (17) in Li & Ma (1983). The highest flux was observed on 2008 February 1 at a significance of 8.0σ .

In searching for time variability, the data set was divided into nine subsets, one per observing night. In Figure 2 we show both the light curve above the analysis threshold (150–350 GeV) and in the energy range at which MAGIC has the highest sensitivity for a variability search (>350 GeV). The low-energy range shows no significant variability with a χ_r^2 of 12.6/8 (probability of $P = 0.13$) for a constant fit. Instead, in the energy range above 350 GeV clear variability is found. A fit by a constant has a χ_r^2 of 47.8/8 corresponding to $P = 1.1 \times 10^{-7}$. The correlation

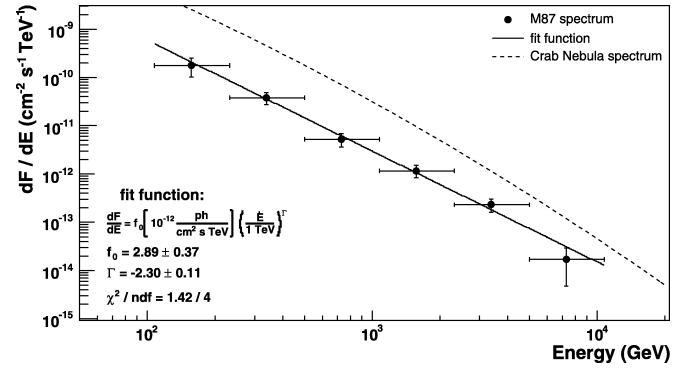


FIG. 3.—Differential energy spectrum of M87 for the total data sample. The horizontal error bars represent width of the energy bins. The best-fit function, assuming a power law, is given by the solid curve. The Crab Nebula spectrum (Albert et al. 2008a) is given by the dashed curve for reference.

coefficient between the two energy bins is $r = -0.25^{+0.40}_{-0.33}$ (1σ errors), suggesting that there is no significant correlation, but we note rather large error bars in the low energy flux bin. We also investigated a night-by-night variability. There are five pairs of observations on consecutive nights in the total data set. We calculated individual probabilities S_i for these pairs to have the same flux level and the corresponding significances. We then computed a combined significance S_{comb} (Bityukov et al. 2006): $S_{\text{comb}} = (\sum S_i) / \sqrt{n}$, with $n = 5$. We interpret the resulting $S_{\text{comb}} = 5.6 \sigma$ as a proof that the flux varies on timescales of 1 day or below. Note that the 1 day variability is claimed from this combined analysis rather than from the 2008 February 1 flare alone. We find our statistics not sufficient enough to determine the flare shape. Given the number of the observed changes in the flux level, the data belong to a complex of two, if not three, subflares.

We also looked for shorter time variability, but in none of the observation nights there is a significant flux variation in the two energy bands. A typical example in a 40 minute binning is shown in the inset in Figure 2 for 2008 February 1.

The averaged differential energy spectrum of M87 (Fig. 3) extends from ~ 100 GeV to ~ 10 TeV and can be well approximated by a power law:

$$\frac{dF}{dE} = (2.89 \pm 0.37) \times 10^{-12} \left(\frac{E}{1 \text{ TeV}} \right)^{-2.30 \pm 0.11} \frac{1}{\text{TeV cm}^2 \text{ s}}.$$

The errors are statistical only. We estimate an 11% systematic uncertainty in the normalization and 0.20 for the spectral index (Albert et al. 2008a). The measured values are in good agreement with the H.E.S.S. (spectral index $\Gamma = -2.2 \pm 0.15$; Aharonian et al. 2006) and VERITAS ($\Gamma = -2.31 \pm 0.17$; Acciari et al. 2008) results. The observed spectrum is not significantly affected by the evolving extragalactic background light (EBL) due to the proximity of M87 (Neronov & Aharonian 2007). To investigate a possible hardening of the spectrum with increasing absolute flux level, we divided the data sample into *high* and *low* state subsamples. The high sample comprises the two nights with the highest flux above 350 GeV (February 1 and 8), while the low state comprises the nights of lower flux data (January 30, February 2, 4, and 11). Both the high and low state spectra (Fig. 4) can be well described by a power law:

$$\frac{dF}{dE} = f_0 \left(\frac{E}{1 \text{ TeV}} \right)^{\Gamma} \frac{10^{-12}}{\text{cm}^2 \text{ s TeV}},$$

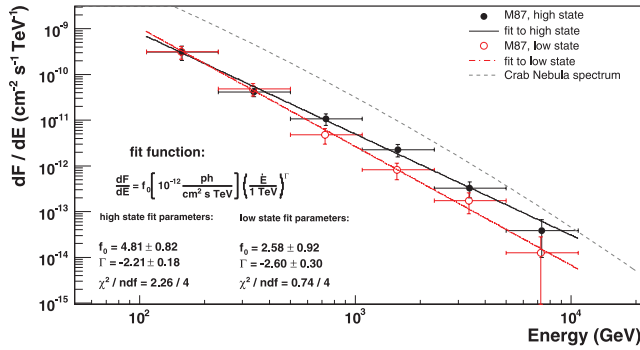


FIG. 4.—Differential energy spectra of M87 divided into high (filled circles) and low (open circles) states. See text for details. The best-fit functions, assuming power laws, are given by the black solid and red dash-dotted curves, respectively.

with $f_0^{\text{high}} = (4.81 \pm 0.82)$, $\Gamma^{\text{high}} = (-2.21 \pm 0.18)$ and $f_0^{\text{low}} = (2.58 \pm 0.92)$, $\Gamma^{\text{low}} = (-2.60 \pm 0.30)$ for the high and low states, respectively. There is a marginal hardening of the spectral index with the higher flux on the level of 1–2 standard deviations, depending on the way the significance is calculated. This hardening is not significant, which can be a consequence of the fact that the two flux levels (states) differ by less than a factor of 2.

4. DISCUSSION

M87 is the only nonblazar radio galaxy known to emit VHE γ -rays and one of the best-studied extragalactic black hole systems. To enable long-term studies and assess the variability timescales of M87, the H.E.S.S., VERITAS, and MAGIC collaborations established a regular, shared monitoring of M87 and agreed on mutual alerts in case of a significant detection. During the MAGIC observations, a strong signal of 8σ significance was found on 2008 February 1, triggering the other IACTs as well as *Swift* observations. For the first time, we assessed the energy spectrum below 250 GeV, where our observations can be well described by a power law that shows no hint of any flattening.

Our analysis revealed a variable (significance: 5.6σ) night-to-night γ -ray flux above 350 GeV, while no variability was found in the 150–350 GeV range. We confirm the $E > 730$ GeV short-time variability of M87 reported by Aharonian et al. (2006). The observed variability timescale is on the order of or

even below 1 day, restricting the emission region to a size of $R \leq \Delta t c \delta = 2.6 \times 10^{15} \text{ cm} = 2.6 \delta R_s$. The Doppler factor δ is only relevant for an emission region not expanding while traversing the jet. In case of an expanding-jet hypothesis, the initial radius of the expanding shell is given by $R^* < c \Delta t$. The emission can occur very close to the BH, provided that the ambient photon density is low enough as to allow the propagation of VHE γ -rays. Otherwise the emission region must be located farther away from the BH. In the latter case, the variability constraints can be met only if the emitting plasma does not substantially expand while traversing the jet, or if it moves with $\delta \geq 10$.

There exists no lower limit on the size of HST-1, and thus the flux variability cannot dismiss HST-1 as possible origin of the TeV flux. During the MAGIC observations, however, HST-1 was at a historically low X-ray flux level, whereas at the same time the luminosity of the M87 core was at a historical maximum (D. Harris 2008, private communication). This strongly supports the core of M87 as the VHE γ -ray emission region.

Our data alone cannot put strong constraints on VHE γ -ray emission models. The relatively hard VHE spectrum found for M87 ($\Gamma \approx -2.3$) is not unique among the extragalactic VHE γ -ray sources if one considers intrinsic spectra, i.e., EBL corrected. Also, we did not measure a high-energy spectral cutoff. The found marginal spectral hardening may be interpreted as a similarity to other blazars detected at VHE, where such hardening has often been observed.

Our results show that a dense TeV monitoring, as exercised by ground-based IACTs, has revealed highly interesting rapid flares in M87. This fastest variability observed so far in TeV γ -rays observed in M87 restricts the size of the γ -emission region to the order of R_s of the central BH of M87 and suggests the core of M87 rather than HST-1 as the origin of the TeV γ -rays. Results from the entire monitoring campaign, comprising data from other IACTs, will appear in a separate paper.

We would like to thank the Instituto de Astrofísica de Canarias for the excellent working conditions at the Observatorio del Roque de los Muchachos in La Palma. The support of the German BMBF and MPG, the Italian INFN, and Spanish MCI is gratefully acknowledged. This work was also supported by ETH research grant TH 34/043, by the Polish MNiSzW grant N N203 390834, and by the YIP of the Helmholtz Gemeinschaft. We thank Dan Harris for providing preliminary results on *Chandra* observations.

REFERENCES

- Acciari, V. A., et al. (VERITAS Collaboration). 2008, *ApJ*, 679, 397
 Aharonian, F. A. 2000, *NewA*, 5, 377
 Aharonian, F. A., et al. (HEGRA Collaboration). 2003, *A&A*, 403, L1
 Aharonian, F. A., et al. (H. E. S. S. Collaboration). 2006, *Science*, 314, 1424
 Albert, J., et al. (MAGIC Collaboration). 2007, *Nucl. Instrum. Methods Phys. Res. A*, 583, 494
 ———. 2008a, *ApJ*, 674, 1037
 ———. 2008b, *Nucl. Instrum. Methods Phys. Res. A*, 558, 424
 ———. 2008c, preprint (astro-ph/0702475)
 Beall, J. H., & Bednarek, W. 1999, *ApJ*, 510, 188
 Biretta, J. A. 1996, in *ASP Conf. Ser. 100, Energy Transport in Radio Galaxies and Quasars*, ed. P. E. Hardee et al. (San Francisco: ASP), 187
 Bitunov, S., et al. 2006, preprint (physics/0612178)
 Curtis, H. D. 1918, *Publ. Lick Obs.*, 13, 31
 Dar, A., & Laor, A. 1997, *ApJ*, 478, L5
 Daum, A., et al. (HEGRA Collaboration). 1997, *Astropart. Phys.*, 8, 1
 Fanaroff, B. L., & Riley, J. M. 1974, *MNRAS*, 167, 31P
 Forman, W., et al. 2007, *ApJ*, 665, 1057
 Georganopoulos, M., Perlman, E. S., & Kazanas, D. 2005, *ApJ*, 634, L33
 Ghisellini, G., Tavecchio, F., & Chiaberge, M. 2005, *A&A*, 432, 401
 Harris, D. E. 2006, *ApJ*, 640, 211
 Hillas, A. M. 1985, in *Proc. 19th Int. Cosmic Ray Conf. (La Jolla)*, 3, 445
 Honda, M., & Honda, Y. S. 2007, *ApJ*, 654, 885
 Lenain, J.-P., Boisson, C., Sol, H., & Katarzyński, K. 2008, *A&A*, 478, 111
 Li, T.-P., & Ma, Y.-Q. 1983, *ApJ*, 272, 317
 Macchetto, F., et al. 1997, *ApJ*, 489, 579
 Macri, L. M., et al. 1999, *ApJ*, 521, 155
 Mannheim, K. 1993, *A&A*, 269, 67
 Maraschi, L., Ghisellini, G., & Celotti, A. 1992, *ApJ*, 397, L5
 Marshall, H. L., et al. 2002, *ApJ*, 564, 683
 Mücke, A., & Protheroe, R. J. 2001, *Astropart. Phys.*, 15, 121
 Neronov, A., & Aharonian, F. A. 2007, *ApJ*, 671, 85
 Perlman, E. S., Harris, D. E., & Biretta, J. A. 2003, *ApJ*, 599, L65
 Protheroe, R. J., Donea, A.-C., & Reimer, A. 2003, *Astropart. Phys.*, 19, 559
 Rieger, F. M., & Aharonian, F. A. 2008, *A&A*, 479, L5
 Stawarz, Ł., Sikora, M., & Ostrowski, M. 2003, *ApJ*, 597, 186
 Tavecchio, F., & Ghisellini, G. 2008, *MNRAS*, 385, L98
 Tescaro, D., et al. (MAGIC Collaboration). 2007, preprint (arXiv:0709.1410)
 Tsvetanov, Z. I., et al. 1998, *ApJ*, 493, L83
 Wilson, A. S., & Yang, Y. 2002, *ApJ*, 568, 133