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Monitoring of the radio galaxy M 87 at Very High Energy with MAGIC during a low emission state between 2012 and 2015

C. Arcaro[1], P. Bangale[2], M. Manganaro[3], D. Mazin[2,4], P. Colin[2], Ie. Vovk[2], K. Mannheim[5] for the MAGIC Collaboration and K. Hada[6], H. E. Jermak[7], J. P. Madrid[8], F. Massaro[9], S. Richter[10], F. Spanier[10] and R. C. Walker[11]

[1]Università di Padova and INFN, I-35131 Padova, Italy
email: cornelia.arcaro@pd.infn.it

[2]Max-Planck-Institut für Physik, D-80805 München, Germany
[3]Inst. de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain; Universidad de La Laguna, Dpto. Astrofísica, E-38206 La Laguna, Tenerife, Spain
[4]also at Japanese MAGIC Consortium
[5]Universität Würzburg, D-97074, Würzburg, Germany
[6]Mizusawa VLBI Observatory, National Astronomical Observatory of Japan, 2-12 Hoshigaoka-cho, Mizusawa, Oshu, Iwate 023-0861, Japan
[7]Astrophysics Research Institute, Liverpool John Moores University, Liverpool, UK
[8]CSIRO, Astronomy and Space Science, PO Box 76, Epping NSW 1710, Australia
[9]Dipartimento di Fisica, Università degli Studi di Torino, via Pietro Giuria 1, I-10125 Torino, Italy
[10]North-West University, Potchefstroom, South Africa [11]National Radio Astronomy Observatory, Socorro, NM 87801, USA

Abstract. We present the preliminary results from observing the nearby radio galaxy M 87 for 156 hours (between the years 2012 and 2015) with the MAGIC telescopes, which lead to a significant very high energy (VHE, $E > 100\,\mathrm{GeV}$) detection of the source in quiescent states each year. Our VHE analysis combined with quasi-simultaneous data at other energies (from gamma-rays, X-rays, optical and radio) provides a unique opportunity to study the source variability and its broadband spectral energy distribution, which is found to disfavour a one-zone synchrotron/synchrotron self-Compton model. Therefore, other alternative scenarios for the photon emission are explored. We also find that the VHE emission is compatible with being produced close to the source radio core as previous data already indicated. A detailed paper presenting full results of the observing campaign is in preparation.

Keywords. BL Lacertae objects: individual: M 87 - galaxies: active - galaxies: jets - gamma rays: observations - radiation mechanisms: nonthermal

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Messier 87, commonly known as M 87, is a giant elliptical radio galaxy of Fanaroff-Riley-I-type (FR I; Fanaroff & Riley 1974), located in the nearby Virgo Cluster, at a distance $\sim 16\,\mathrm{Mpc}$ (e.g. Blakeslee *et al.* 2009, Bird *et al.* 2010), and powered by a super-massive black hole.

The relativistic jet of M 87 is misaligned with respect to our line of sight by an angle between $5-25°$ (Biretta *et al.* 1999, Acciari *et al.* 2009), allowing the study of the jet during its evolution from the core to the extended lobe. The jet features several knots along his length, the inner knot being HST-1 located at $0.85''$ from the core, that have been resolved in radio, optical and X-ray bands (Perlman *et al.* 2001, Wilson & Yang 2002).

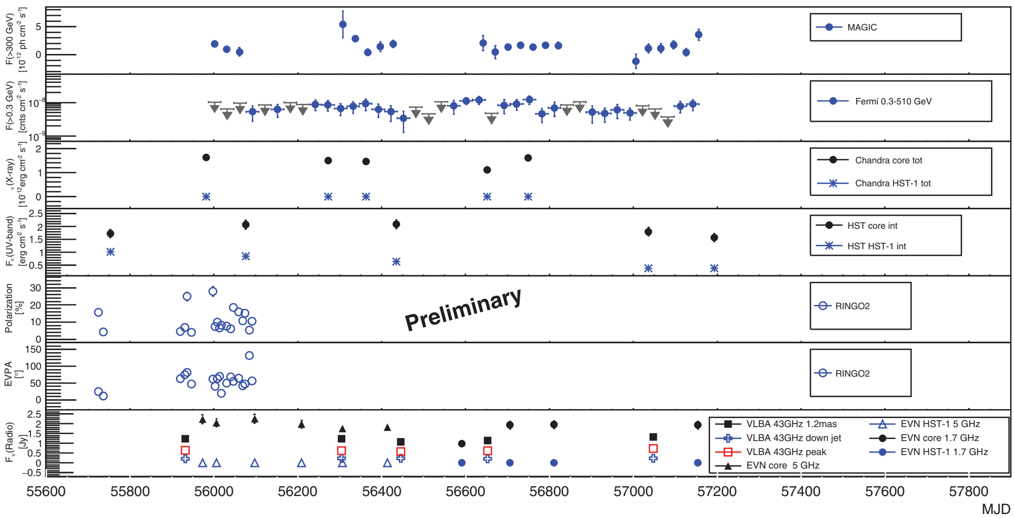

Figure 1. *From top to bottom:* VHE (filled circles) and HE gamma-ray (filled circles) data from MAGIC and *Fermi*-LAT; Galactic absorption corrected X-ray data (core: filled circles; HST-1: asterics) from *Chandra*; optical data in the UV band (core: filled circles; HST-1: asterics) from HST are corrected for extinction (Cardelli *et al.* 1989). Optical polarimetry data (open circles) taken with V+R filter by Liverpool telescope with RINGO2; radio data at 43 GHz by VLBA (1.2 mas: filled squares; peak: open squares; down jet: open cross) and EVN at 1.7 and 5 GHz (core: filled/open triangles; HST-1: filled/open circles). Upper limits of 95% confidence level are indicated by downward arrows. The light curves are daily binned except VHE and HE gamma rays, where a monthly and a 30-day binning were applied, respectively.

Here we present the MAGIC VHE monitoring dataset of M 87 between 2012 and 2015 together with multiwavelength (MWL) data from high energy (HE; $100\,\mathrm{MeV} < E < 100\,\mathrm{GeV}$), gamma rays to radio frequencies both of the core and HST-1. No major flare was detected in that period in any of the observed bands, which allows us to study the source in quiescent flux state. The data quality is sufficient to constrain some emission models and to study the broad band spectral energy distribution (SED) of M87.

MAGIC is a stereoscopic system of two 17-m diameter IACTs situated at the Roque de los Muchachos, on the Canary island of La Palma (28.75°N, 17.86°W) at a height of 2200 m above sea level, with an integral sensitivity of $(0.66 \pm 0.03)\%$ of the Crab nebula flux above 220 GeV in 50 hrs at low zenith angles (Aleksić *et al.* 2016). M87 observations were performed between December and July, in each year from 2012 to 2015 at zenith angles ranging from 15° to 50° during dark time and under Moon light conditions. After quality cuts, a total of 157 hrs of effective observation time of data were used for further analysis.

The MWL dataset presented in Fig. 1 shows no hint for any enhanced activity between 2012 and 2015. We note however that the monitoring in VHE, X-rays, optical and radio was not very frequent, wherefore it cannot be fully excluded that flaring periods took place in the last years.

The positions of the excess of the VHE emission obtained from observations by MAGIC (RA: $12^{\mathrm{h}}30^{\mathrm{m}}49.54^{\mathrm{s}}{\pm}0.94^{\mathrm{s}}{}_{\mathrm{stat}}4.8^{\mathrm{s}}{}_{\mathrm{sys}}$ Dec: $12°23'38.90''{\pm}14.65''_{\mathrm{stat}}{\pm}1.2''_{\mathrm{sys}}$) between 2012 and 2015, by H.E.S.S. (RA: $12^{\mathrm{h}}30^{\mathrm{m}}47.2^{\mathrm{s}} \pm 1.4^{\mathrm{s}}{}_{\mathrm{stat}} \pm 1.3^{\mathrm{s}}{}_{\mathrm{sys}}$, Dec: $12°23'51'' \pm 19''_{\mathrm{stat}} \pm 20''_{\mathrm{sys}}$; Aharonian *et al.* 2006) and VERITAS (RA: $12^{\mathrm{h}}30^{\mathrm{m}}46^{\mathrm{s}} \pm 4^{\mathrm{s}}{}_{\mathrm{stat}} \pm 6^{\mathrm{s}}{}_{\mathrm{sys}}$, Dec: $12°23'21'' \pm 50''_{\mathrm{stat}} \pm 1'30''_{\mathrm{sys}}$; Acciari *et al.* 2008) are compatible within the errors. The Very Large Array (VLA) radio telescope image taken at 330 MHz (Owen *et al.* 2000)

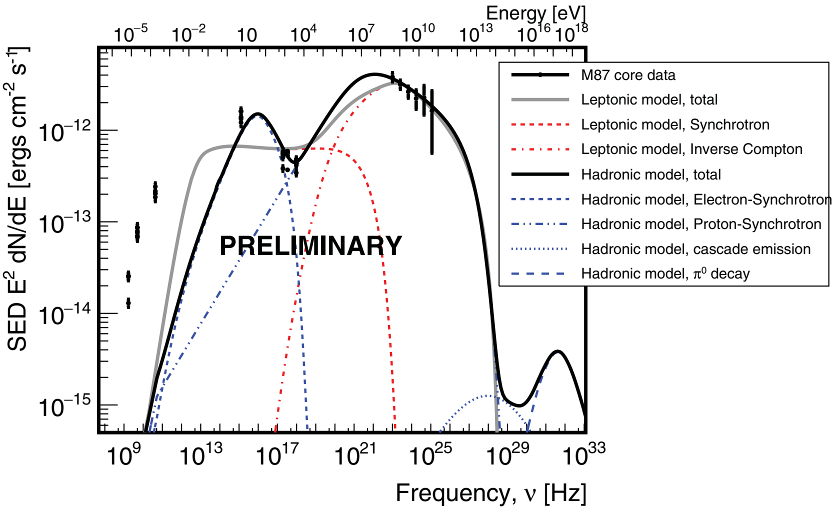

Figure 2. Averaged SED (black points) of the radio core of M87 compiled from quasi-simultaneous 2012-2015 MWL observations: HE gamma-ray data (*Fermi*-LAT); Galactic absorption corrected X-ray (*Chandra*), optical data in the UV band (HST) corrected for extinction (Cardelli *et al.* 1989), radio data at 1.7 GHz and 5 GHz (EVN) and at 43 GHz (VLBA). The models represent two possible scenarios, where the GeV-TeV is either dominated by SSC emission (leptonic case; black solid line) or by the synchrotron radiation of the relativistic protons (hybrid case; gray solid line).

is used as a reference, indicating that the VHE emission is located close to the radio core (RA: $12^{h}30^{m}49.42^{s}$, Dec: $12°23'28.04''$; `http://images.nrao.edu/57`center of radio image taken as reference). The upper limit for an extended VHE emission at 99.9% confidence level of 0.042°, corresponding to 11.5 kpc is shown with previous results obtained from H.E.S.S. observations (0.05°, i.e., 13.7 kpc).

As no clear variability in the TeV regime is detected, the model constraints are not as strict. We assume the relevant parts connected to the TeV gamma-ray emission zone to be the HE gamma-ray and the X-ray data detected for the core region, while radio data from the Very Long Baseline Array (VLBA) and the European VLBI Network (EVN) originate from a larger region. The optical data from Hubble Space Telescope (HST), detected from the core of M 87 presumably originate much closer to the black hole and where the jet is launched. We are, therefore, modelling the X-ray, GeV and TeV data, while the radio to optical data are considered to be upper limits to our models.

The applied model was designed as a hybrid model and can cover the range from purely leptonic scenarios to the full photo-hadronic reaction chain. The fully time-dependent implementation is based on the geometry of Weidinger & Spanier 2010. The acceleration mechanism and the implementation of all leptonic processes was adopted from Richter & Spanier 2016 and the photo-hadronic framework was implemented following Hümmer *et al.* (2010).

In the leptonic model the GeV-TeV emission is dominated by the inverse Compton emission, while radio to X-ray emission is synchrotron emission from the same electron population. In the hybrid model, the parts from radio to soft X-rays also originate from synchrotron emission of electrons. Due to the higher magnetic field and the assumption of protons being injected into the acceleration zone, the higher energies are dominated by synchrotron emission of protons in this case.

We note that *Chandra* data ($10^{17}-10^{18}$) Hz are in the sensitive area of the transition between the two bumps in the SED. In the leptonic model we did not succeed to properly match the *Chandra* photon index, that seems to be softer than in the model. The reason for that is a rather flat synchrotron self-Compton (SSC) spectrum in the Inverse Compton (IC) regime up to 10 TeV without an apparent cut-off in the data. This requires high maximum energies for the electron population, leaving the IC in the Klein-Nishina regime and resulting in a different, softer photon index in the IC regime. The high HE flux in comparison to the X-ray flux adds to the difficulties and requires a high particle density. The resulting Doppler factor is low, as one might expect so close to the black hole. Summarising, a homogeneous leptonic model is able to describe the five orders in magnitude flat photon spectrum in HE and VHE gamma rays (*Fermi*-LAT and MAGIC) but it must be pushed to extreme limits and still has possible troubles in reproducing the X-ray data.

In the hybrid scenario it is easier to fit the available data. However, the number of parameters is higher than in the leptonic case and the two components (synchrotron from electrons and synchrotron from protons) are basically independent of each other, as their densities are unrelated. On the other hand, the hybrid model has a clear prediction on the flux of π_0 decay at $\sim$10 PeV, which can be probed by instruments like HAWC after a long exposure.

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