Highlights of the MAGIC AGN program

Julian Sitarek[*]

University of Łódź, PL-90236 Lodz, Poland

E-mail: jsitarek@uni.lodz.pl

for the MAGIC Collaboration

MAGIC is a system of two Cherenkov telescopes designed to perform observations of gamma rays with energies from about 50 GeV to tens of TeV. A low energy threshold and an excellent low energy performance make it a powerful instrument for studies of high energy processes in Active Galactic Nuclei (AGN). The MAGIC Collaboration dedicates about 40% of the telescopes' time to such observations, both monitoring of known emitters, and Target of Opportunity observations of flaring events. In this presentation we will discuss the recent highlights of the MAGIC AGN program. In particular, multi year monitoring of radio galaxies, such as M87, and strong peculiar blazars, such as PG 1553+113, will be presented together with new discoveries based on the Target Of Opportunity program.

[*]Speaker.

1. Introduction

AGN (Active Galactic Nuclei) are the central parts of some of the galaxies, from which broadband, mainly non-thermal and highly variable radiation is observed. They are believed to be powered by accretion of matter on a rotating black hole, which is also causing in some subclasses of those objects occurrence of superrelativistic outflows (the so-called jets) from their central engine. The broadband emission produced in AGN jets consists of two broad peaks; one in IR to X-ray range, and the second one in GeV-TeV γ rays. While the first peak is commonly attributed to the synchrotron radiation, the origin of the second peak is still being disputed. In leptonic models the second peak is produced by inverse Compton scattering by electrons of ambient radiation fields, either internal to the jet (e.g. synchrotron-self-Compton model, see e.g. [1]), or external to it (see e.g. [2]). AGN are observationally classified into multiple types. The most common in VHE (very-high-energy, $\gtrsim 100\,\mathrm{GeV}$) γ-ray astronomy being BL Lacs, in which the jet direction is aligned with the line of sight to the observer causing strong enhancement of the observed flux by relativistic boosting. They are further divided into HBL, IBL and LBL (high, intermediate and low energy peaked BL Lacs respectively) sub-classes depending on the location of the SED peaks. Flat spectrum radio quasars (FSRQ), also strongly relativistically boosted, are intrinsically more powerful than BL Lacs, however their peaks are even more shifted to the lower energies, making their detection at VHE γ rays challenging. The radiation fields external to the jet in FSRQ are also stronger than in BL Lacs, making those sources both more interesting and much more complicated. FSRQ and BL Lacs together are called blazars. Relativistically non-boosted counterparts of blazars are believed to be radio galaxies in which the jet orientation has a large angle to our viewing direction. The VHE γ-ray observations of AGN are giving us unique information about the highest energy processes occurring in them, and thus are crucial for understanding the extreme physical conditions in the jet of AGN.

MAGIC (*Major Atmospheric Gamma Imaging Cherenkov*) is a system of two 17m diameter Imaging Atmospheric Cherenkov Telescopes [3]. The telescopes are located at the height of 2200 m a.s.l. at the observatory of the Roque de los Muchachos in the Canary Island of La Palma (28°N, 18°W). The first MAGIC telescope (MAGIC-I) performs observations since 2004. Starting from 2009, when the construction of the second telescope (MAGIC-II) finished, both telescopes are working together in the so-called stereoscopic mode. Large mirror area, combined with the stereo observations, provides unprecedented performance of the instrument at the lowest energies, namely around and below 100 GeV [4]. The low energy threshold ($\sim 50-60$ GeV at low zenith angle observations), combined with Northern hemisphere location (exploiting ample multiwavelength coverage of Northern sources) makes it an excellent instrument for observations of the VHE γ rays from AGN objects. In this contribution we present the AGN observation program of MAGIC and discuss a few selected recent results.

2. MAGIC AGN program

Over the last 25 years the VHE γ-ray astronomy of AGN objects evolved from a single known source to a moderately large catalog of 70 sources [5]. MAGIC has detected γ-ray emission from more than a half (39/70) of those sources (see the left panel of Fig. 1), including the two most distant

($z \sim 1$) sources. Thanks to the excellent low energy performance of MAGIC, it is not surprising
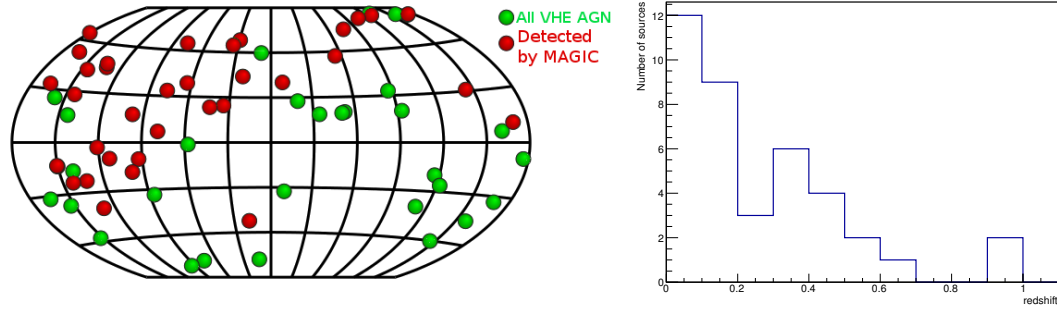

Figure 1: Left panel: extragalactic VHE γ-ray sky. Green circles show all the currently detected in VHE γ rays AGN, while those from which VHE γ-ray has been observed with MAGIC are shown with red circles. Figure created using maps from [5]. Right panel: the redshift distribution of AGN detected with MAGIC.

that this list contains also all but one currently known VHE γ-ray FSRQs: PKS1510-089 [6], 3C 279 [7], 3C +21.35 [8], B0218+357 [9] and PKS1441+25 [10]. The list, status as of June 2017, of extragalactic sources detected with MAGIC is shown in Table 1.

The increase of number of sources observed in the recent years in VHE γ-ray range motivated the MAGIC Collaboration to modify the observation strategy from source hunting towards deeper and more goal-oriented observations of few selected objects. Yearly, the MAGIC Collaboration is devoting about 40% of the total telescopes' time (i.e. ~ 380 hr of dark hours and ~ 200 hr of time during moonlight conditions) on observations of AGN objects. The MAGIC AGN program involves:

- long term monitoring of selected sources, among which the FSRQ PKS1510-089 (see also [11]), the HBL PG 1553+113, and the radio galaxy M87.

- expanding the catalog of poorly populated in VHE γ-rays non-HBL AGN classes.

- broadband multiwavelength campaigns on strong γ-ray emitters such as Mrk 421 or Mrk 501.

- vast (over 100 hr yearly) follow up program of mainly GeV, X-ray and optical alerts (see also [12, 13]).

- usage of selected AGN objects for fundamental physics studies, such us constraints on the extragalactic background light radiation (see also [14]) or search for AGN halos due to intergalactic magnetic fields.

The MAGIC AGN observations are usually supported by GeV observations of *Fermi*-LAT [15], X-ray and UV observations of *Swift* [16] performed via ToO alerts, in-house optical monitoring and follow-up with KVA telescope [17]. Often also lower frequencies (IR, radio) and optical polarization information is gathered during such studies.

Name	RA	Dec	z	period	reference
1ES0033+595	00 35 16.8	+59 47 24.0	0.467	2009.08-09	[18]
S20109+22	01 12 05.8	+22 44 39	>0.35	2015.07	[19]
RGBJ0136+391	01 36 32.5	+39 06 00	>0.27	2009.11	in prep.
B0218+357	02 21 05.5	+35 56 14	0.954	2014.07	[9]
3C 66A	02 22 41.6	+43 02 35.5	>0.3347	2007.08-12	[20]
IC310	03 16 43.0	+41 19 29	0.0189	multiple	[21]
NGC1275	03 19 48.1	+41 30 42	0.017559	multiple	[22]
1ES0647+250	06 50 46.5	+25 03 00	0.45 ± 0.02	2009-2011	in prep.
S50716+714	07 21 53.4	+71 20 36	0.31 ± 0.08	multiple	[23]
1ES0806+524	08 09 59	+52 19 00	0.138	2011.01-03	[24]
RBS0723	08 47 12.9	+11 33 50	0.198	2014.01	in prep.
S40954+65	09 58 47.00	+65 33 55	>0.45	2015.02	[26]
1ES1011+496	10 15 04.1	+49 26 01	0.212	multiple	[27]
Mrk421	11 04 19	+38 11 41	0.031	multiple	[28]
Mrk180	11 36 26.4	+70 09 27	0.045	2006.03	[29]
RXJ1136.5+6737	11 36 30.1	+67 37 04	0.1342	2014.01-05	[30]
1ES1215+303	12 17 48.5	+30 06 06	0.13	2011.01-02	[31]
1ES1218+304	12 21 26.3	+30 11 29	0.182	multiple	[32]
MS1221.8+2452	12 24 24.2	+24 36 24	0.218	2013.04-05	[33]
4C+21.35	12 24 54.4	+21 22 46	0.432	2010.06	[8]
M87	12 30 47.2	+12 23 51	0.0044	multiple	[34]
3C279	12 56 11.1	-05 47 22	0.5362	multiple	[7]
PKS1424+240	14 27 00	+23 47 40	0.604	2009-2011	[35]
H1426+428	14 28 32.6	+42 40 21	0.129	2013	in prep.
PKS1441+25	14 43 56.9	+25 01 44	0.940	2015	[10]
PKS1510-089	15 12 52.2	-09 06 21.6	0.361	multiple	[6]
PG1553+113	15 55 44.7	+11 11 41	0.43-0.58	multiple	[36]
Mrk501	16 53 52.2	+39 45 37	0.034	multiple	[37]
H1722+119	17 25 04.3	+11 52 15	>0.35	2013.05	[38]
1ES1727+502	17 28 18.6	+50 13 10	0.055	2011.05-06	[39]
1ES1741+196	17 44 01.2	+19 32 47	0.084	2010.04-2011.05	[40]
OT 081	17 51 32.8	+09 39 00	0.322	2016.07	[41]
1ES1959+650	19 59 59.8	+65 08 55	0.048	multiple	[42]
MAGIC J2001+435	20 01 13.5	+43 53 03	0.18 ± 0.04	2010.06	[43]
1ES2037+521	20 39 23.5	+52 19 50	0.054	2016.09	[44]
PKS2155-304	21 58 52.7	-30 13 18	0.116	2006.07-08	[45]
BL Lacertae	22 02 43.3	+42 16 40	0.069	multiple	[46]
B32247+381	22 50 06.6	+38 25 58	0.1187	2010.09-10	[47]
1ES2344+514	23 47 04.9	+51 42 17	0.044	multiple	[48]

Table 1: List of 39 sources from which MAGIC has observed γ-ray emission in years 2004-2017. Individual columns: name, right ascension and declination (taken from [5]), redshift, observation time period, reference.

2.1 Monitoring of M87

M87, located at the distance of $\sim 16\,$Mpc [49] is the best studies radio galaxy known in VHE γ rays. MAGIC performs a regular, deep monitoring of M87. In years 2012-2015 in total over 150 hr were gathered from this source, allowing an independent detection with above 5σ signal in each year. Daily and monthly light curve does not show any significant variability. The spectral energy distribution of the source connects smoothly with the *Fermi*-LAT measurements performed in the same time period (see Fig. 2). The SED of the source is studied in terms of a leptonic model based
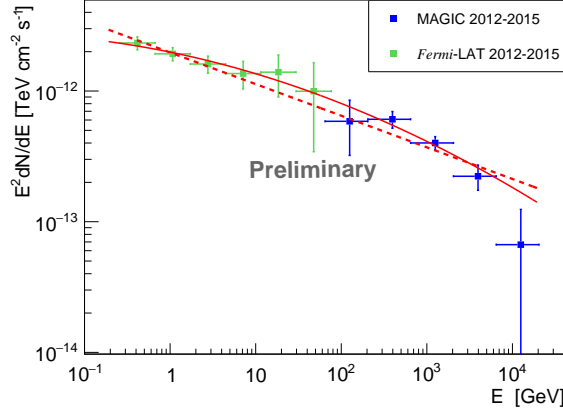
Figure 2: Spectral energy distribution of M87 measured by MAGIC (blue) and *Fermi*-LAT (green). Dashed and solid lines show a joined spectral fit with power-law and log-parabola spectral shape respectively.

on scenario presented in [50]. The observed multiwavelength data are consistent with a constant injection of accelerated particles at the distances of a few hundred gravitational radii from the black hole. The spectrum of the electrons evolves as the particles propagate along the jet cooling down in SSC scenario. The details of this study will be discussed in a separate publication.

2.2 Monitoring of PG 1553+113

PG 1553+113 is a distant ($z \sim 0.5$, [51]) HBL. Quasi-periodic oscillations with a period of 2.18 ± 0.08 year has been observed from this source in GeV, optical and partially also in radio bands [52]. PG 1553+113 is being observed by the MAGIC telescopes already since over 10 years (see Fig. 3), however the early observations were irregular and biased by observations of flares. Regular, denser monitoring is ongoing since 2015. In order to explain the broadband data we consider a geometrical model of emission for periodic blazar [53]. According to it the variability is produced by the modulation of the observation angle due to jet precession. The details of this study will be discussed in a separate publication.

2.3 Expanding the population of LBLs and IBLs

Despite the relatively large population of HBLs in VHE γ rays still only a handful of LBLs and IBLs are known at those energies. The small number is most probably an observational bias, as due to the shift of the high energy peak to lower energies in those sources, they are difficult targets for IACTs. MAGIC, due to its excellent low energy performance can contribute to the studies of those sources and their connection to HBLs and FSRQs.
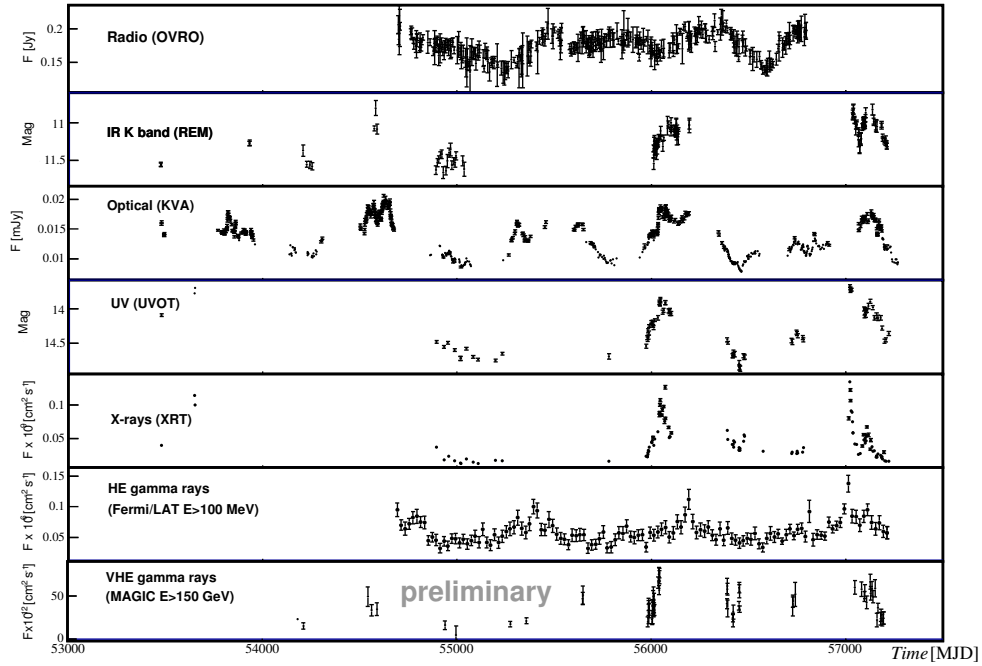
Figure 3: Multiwavelength light curve of PG1553+113. From top to bottom: Radio, IR, optical, UV, X-ray, GeV and sub-TeV energy ranges. *Fermi*-LAT data are binned in 20 days bins.

OT 081 is a blazar classified as a LBL [54]. MAGIC observations of this source performed during elevated GeV, X-ray and optical emission revealed a significant γ ray excess from the direction of this source [41], see the right panel of Fig. 4. S2 0109+22 is an IBL located at an unknown
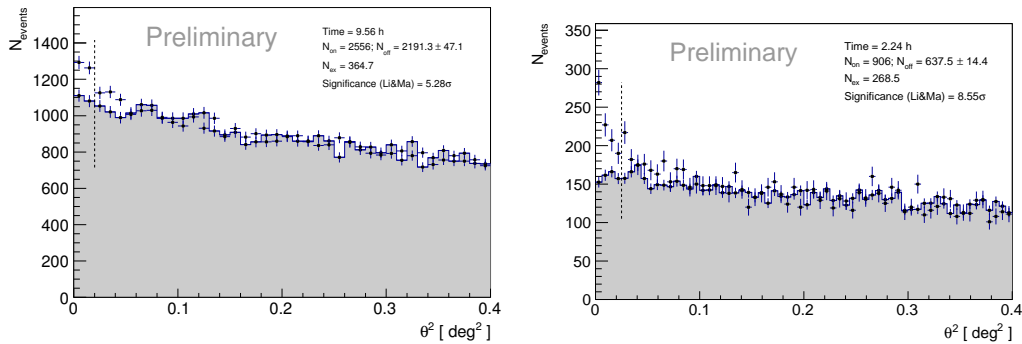

Figure 4: Distribution of the distance from the nominal source position (points) and the background estimation (shaded area). Left panel: S2 0109+22 observations in July 2015. Right panel: OT 081 observations in July 2016.

distance. The observations by MAGIC during a high state in July 2015 led to a detection of a significant γ-ray signal from this source [19], see the left panel of Fig. 4.

3. Conclusions

For the last 13 years the MAGIC telescopes have been investing a significant fraction of their

observation time in studies of AGN objects. MAGIC has detected VHE γ-ray emission from more than a half of all the currently known in this range AGN objects, for 27 objects for the first time. Recently the MAGIC AGN program is more focused on deep, multiwavelength studies of known VHE γ-ray emitters, and on search for new γ-ray emitters in poorly populated in this range AGN classes. MAGIC will continue those studies in the future preparing for the CTA era.

Acknowledgements

References

[1] Rees, M. J. 1967, MNRAS, 137, 429

[2] Dermer, C. D., & Schlickeiser, R. 1993, ApJ, 416, 458

[3] Aleksić, J., Ansoldi, S., Antonelli, L. A., et al. 2016, Astroparticle Physics, 72, 61

[4] Aleksić, J., Ansoldi, S., Antonelli, L. A., et al. 2016, Astroparticle Physics, 72, 76

[5] Wakely, S. P., & Horan, D., TeVCat, http://tevcat2.uchicago.edu/

[6] Aleksić, J., Ansoldi, S., Antonelli, L. A., et al. 2014, A&A, 569, A46

[7] MAGIC Collaboration, Albert, J., Aliu, E., et al. 2008, Science, 320, 1752

[8] Aleksić, J., Antonelli, L. A., Antoranz, P., et al. 2011, ApJL, 730, L8

[9] Ahnen, M. L., Ansoldi, S., Antonelli, L. A., et al. 2016, A&A, 595, A98

[10] Ahnen, M. L., Ansoldi, S., Antonelli, L. A., et al. 2015, ApJL, 815, L23

[11] Sitarek, J. et al., in this Conference PoS(ICRC2017)657

[12] Glawion, D. et al., in this Conference PoS(ICRC2017)662

[13] Zacharias, M. et al., in this Conference PoS(ICRC2017)655

[14] Moralejo, A. et al., in this Conference PoS(ICRC2017)604

[15] Atwood, W. B., Abdo, A. A., Ackermann, M., et al. 2009, ApJ, 697, 1071

[16] Burrows, D. N., Hill, J. E., Nousek, J. A., et al. 2004, Proc. SPIE, 5165, 201

[17] Nilsson et al., 2017, submitted

[18] Aleksić, J., Ansoldi, S., Antonelli, L. A., et al. 2015, MNRAS, 446, 217

[19] Mirzoyan, R. 2015, The Astronomer's Telegram, #7844

[20] Aliu, E., Anderhub, H., Antonelli, L. A., et al. 2009, ApJL, 692, L29

[21] Aleksić, J., Antonelli, L. A., Antoranz, P., et al. 2010, ApJL, 723, L207

[22] Aleksić, J., Alvarez, E. A., Antonelli, L. A., et al. 2012, A&A, 539, L2

[23] Anderhub, H., Antonelli, L. A., Antoranz, P., et al. 2009, ApJL, 704, L129

[24] Aleksić, J., Ansoldi, S., Antonelli, L. A., et al. 2015, MNRAS, 451, 739

[25] Mirzoyan, R. 2014, The Astronomer's Telegram, #5768

[26] Mirzoyan, R. 2015, The Astronomer's Telegram, #7080

[27] Ahnen, M. L., Ansoldi, S., Antonelli, L. A., et al. 2016, MNRAS, 459, 2286

[28] Ahnen, M. L., Ansoldi, S., Antonelli, L. A., et al. 2016, A&A, 593, A91

[29] Albert, J., Aliu, E., Anderhub, H., et al. 2006, ApJL, 648, L105

[30] Mirzoyan, R. 2014, The Astronomer's Telegram, #6062

[31] Aleksić, J., Alvarez, E. A., Antonelli, L. A., et al. 2012, A&A, 544, A142

[32] Albert, J., Aliu, E., Anderhub, H., et al. 2006, ApJL, 642, L119

[33] Cortina, J. 2013, The Astronomer's Telegram, #5038

[34] Albert, J., Aliu, E., Anderhub, H., et al. 2008, ApJL, 685, L23

[35] Aleksić, J., Ansoldi, S., Antonelli, L. A., et al. 2014, A&A, 567, A135

[36] Aleksić, J., Alvarez, E. A., Antonelli, L. A., et al. 2012, ApJ, 748, 46

[37] Albert, J., Aliu, E., Anderhub, H., et al. 2007, ApJ, 669, 862

[38] Ahnen, M. L., Ansoldi, S., Antonelli, L. A., et al. 2016, MNRAS, 459, 3271

[39] Aleksić, J., Antonelli, L. A., Antoranz, P., et al. 2014, A&A, 563, A90

[40] Ahnen, M. L., Ansoldi, S., Antonelli, L. A., et al. 2017, MNRAS, 468, 1534

[41] Mirzoyan, R. 2016, The Astronomer's Telegram, #9267

[42] Albert, J., Aliu, E., Anderhub, H., et al. 2006, ApJ, 639, 761

[43] Aleksić, J., Ansoldi, S., Antonelli, L. A., et al. 2014, A&A, 572, A121

[44] Mirzoyan, R. 2016, The Astronomer's Telegram, #9582

[45] Aleksić, J., Alvarez, E. A., Antonelli, L. A., et al. 2012, A&A, 544, A75

[46] Albert, J., Aliu, E., Anderhub, H., et al. 2007, ApJL, 666, L17

[47] Aleksić, J., Alvarez, E. A., Antonelli, L. A., et al. 2012, A&A, 539, A118

[48] Albert, J., Aliu, E., Anderhub, H., et al. 2007, ApJ, 662, 892

[49] Ferrarese, L., Mould, J. R., Kennicutt, R. C., Jr., et al. 2000, ApJ, 529, 745

[50] Asano, K., & Mészáros, P. 2011, ApJ, 739, 103

[51] Danforth, C. W., Keeney, B. A., Stocke, J. T., Shull, J. M., & Yao, Y. 2010, ApJ, 720, 976

[52] Ackermann, M., Ajello, M., Albert, A., et al. 2015, ApJL, 813, L41

[53] Sobacchi, E., Sormani, M. C., & Stamerra, A. 2017, MNRAS, 465, 161

[54] Ackermann, M., Ajello, M., Atwood, W. B., et al. 2015, ApJ, 810, 14