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MAGIC Upper Limits on the VHE emission from Flat Spectrum Radio Quasars

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Blazars are a class of active galactic nuclei (AGN) where the relativistic jet is pointed towards the observer. They are powerful sources of non-thermal radiation from radio to very high energy (VHE, E>100 GeV) gamma-rays. Flat Spectrum Radio Quasars (FSRQs) are a subclass of blazars where there are absorption or emission lines present in the optical spectra. The observed properties of FSRQs are strongly affected by the magnetic field in the accretion disk which changes the UV emission of Broad Line Region (BLR) and infra-red emission from the Dusty Torus. While many (774 as reported in 4FGL-DR2 catalogue [1]) FSRQs have been detected at high energies (HE; E>100 MeV), only a few (9 as of now) could be detected at VHE. In this contribution, we present observations of nine FSRQs performed by Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC)telescopes between 2008 and 2020 with a total observation time of 174 hours. We also include a few observations from the *Fermi*-LAT, *Swift*-UVOT, *Swift*-XRT and optical observations from Kungliga Vetenskapsakademien (KVA) for two sources CTA 102 and B2 2234+28. We also modelled the broad band emission of the sources to look for signatures of absorption in the BLR region and hence to put constraints on the location of the emission region.

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1. Introduction

AGNs are among the most powerful sources in the universe. Blazars are a class of radio-loud active galactic nuclei where the jetted emission is pointed directly or making a small angle with the line of sight of the observer. Blazars are classified depending on the properties of their optical sepctra [26]. BL Lacs belong to the class of blazars with weak or no absorption lines whereas FSRQs have strong emission lines in their optical spectrum. The emission of strong optical and ultra-violet lines of FSRQs are attributed to the rapidly moving gas clouds inside the gravitational potential of the central black hole. The region of gas clouds is referred to as Broad Line Region (BLR).

The typical spectral energy distribution of blazars contains two components. The peak of the low energy component lies in the optical to X-ray region, whereas the peak of the high energy component lies in the MeV to TeV region. The origin of the low energy component is attributed to the synchrotron radiation of the relativistic electrons inside the jet. The origin of the high energy component is under debate. There are two major competitive theories regarding the origin of the high energy component. In the leptonic theory, the relevant process is the inverse Compton scattering of the relativistic electrons with the synchrotron radiation (SSC, synchrotron self-compton) or with external photon fields (EC, external Compton). There are multiple hadronic models based on different scenarios. Protons can interact with soft radiation field (mostly external to the jet photon fields) and produce pions which later on decay into gammas and muons and the muons will eventually decay into electrons. However there are also hadronic models like proton synchrotron where gamma-rays are generated as synchrotron radiation of ultra-high energy protons. The SSC scenario is often used for BL Lacs whereas the EC is commonly used to explain the spectra of FSRQs [21]. The origin of the external photons can be the BLR, the dusty torus or the accretion disk.

The FSRQ are generally observed at high redshift distances. This supports the strong absorption of the γ rays by the EBL (extragalactic background light). FSRQs also show high variability at almost all wavelengths. This makes them ideal candidates for follow-up observations at VHE following high flux states at lower energy bands.

In total, nine FSRQs which have been detected in the VHE energy range so far: 3C 279 [13], 4C +21.35 [4], PKS 1510-089 [16], PKS 1441+25 [2], S30218+35 [3], TON 0599 [20], PKS 0736+017 [17], B2 1420+32 [19] and PKS 0346-27 [27]

In this contribution, we present the VHE γ-ray observation, their data analysis and the corresponding results of the nine FSRQs, namely TXS 0025+197, B2 0234+28, AO 0235+146, 4C55.17, OP 313, CTA 102, B2 2234+28A, TXS 2241+406 and 3C 454.3. We used the data collected by the MAGIC [5], *Fermi*-LAT [7] data simultaneous to the MAGIC observations and optical data from the KVA [25]. We also used the data from the *Fermi*-LAT telescope over a span of 12 years to put the results into context of the average state of these sources.

2. Observations and data analysis

2.1 MAGIC

MAGIC is a system of two Imaging Atmospheric Cherenkov Telescopes (IACTs) situated at the Observatorio del Roque de los Muchachos, on the Canary Island of La Palma, Spain [5]. The energy threshold of the MAGIC telescopes is as low as 50 GeV at low zenith angles [5], making it an ideal instrument for studying the FSRQs. The data have been collected in standard trigger and SUM trigger (SUMT, a low-energy analog trigger [11] used to lower the energy threshold) settings. The analysis procedure for the SUMT is different from the standard trigger data. The sources were observed in wobble mode [14], where four symmetric positions are chosen at 0.4 ° offsets with respect to the camera center. This helps real-time simultaneous background estimation and improves the statistical accuracy of the signal extraction. The data were analysed using the standard MAGIC Analysis and Reconstruction Software (MARS) framework [29]. We used the method in [23] to calculate the upper limits (U. L.) with a 95% confidence level (C. L.)

2.2 *Fermi*-LAT

The Large Area Telescope, on board the *Fermi* Gamma-ray Space satellite, is a pair conversion γ-ray telescope [7]. It detects gamma-ray photons by converting them into electron-positron pairs inside the detector. It has an operational energy range from 20 MeV to over 300 GeV. Dedicated analysis was performed for each of the nine sources using 12 years of *Fermi*-LAT data between August 2018 and August 2020. P8R3 source class events were selected in the energy range of 100 MeV to 1 TeV. The *Fermi* Science Tools (version 11-07-00) based python package Fermipy [28] was used to analyze the data. A similar analysis technique was also used in [22].

2.3 KVA

Optical data were collected from the 35m Celestron telescope attached to the KVA telescope as a part of the Tuorla Blazar Monitoring Program [25]. The monitoring program which was launched in the year 2002 was originally meant for observing TeV candidate BL Lac objects from [10]. However, throughout the years the monitoring sample kept on increasing gradually. The monitoring observations were generally performed twice a week. But, most of the sources in our current work are not part of the main sample. Hence the size sample of the observations is poorer in some cases. Cousins R-filter is used during the said observations.

2.4 *Swift*-UVOT and *Swift*-XRT

The Neil Gehrels *Swift* Observatory [15], launched in 2004 by the National Aeronautics and Space Administration is a space telescope. It is equipped with the following three telescopes: Ultraviolet and Optical Telescope (UVOT; [24]), the Burst Alert Telescope (BAT; [8]), and the X-ray Telescope (XRT; [9]). The observatory collects data in the optical, UV and X-ray energy range. In this work we performed the spectral analysis using *Swift* data from simutaneous MAGIC observational time windows.

Table 1: *Fermi*-LAT FSRQ properties from the 4FGL catalog [1] and *Fermi*-LAT integral flux during MAGIC observations.

Association Name	4FGL Source Name	redshift	R.A. [deg]	decl. [deg]	Integral flux (0.1-1000 GeV) 10^{-8} cm^{-2} s^{-1}	variability index	Integral flux during MAGIC obs. (0.1-1000 GeV) 10^{-8} cm^{-2} s^{-1}
TXS 0025+197	J0028.4+2001	1.552	7.12	20.03	1.2 ± 0.2	27.66	63.4 ± 7.8
B2 0234+28	J0237.8+2848	1.206	39.46	28.80	16.7 ± 0.4	3219.99	80.3 ± 4.2
AO 0235+164	J0238.6+1637	0.94	39.67	16.62	13.1 ± 0.5	65.33	20.1 ± 5.1
4C +55.17	J0957.6+5523	0.902	149.42	55.38	8.5 ± 0.3	32.58	7.3 ± 1.0
OP 313	J1310.5+3221	0.99	197.65	32.35	3.7 ± 0.6	170.41	9.0 ± 5.1
CTA 102	J2232.6+1143	1.037	338.10	11.73	41.6 ± 0.6	14315.21	1030.0 ± 20.0
B2 2234+28A	J2236.3+2828	0.790	339.08	28.45	6.6 ± 0.3	387.65	16.9 ± 4.8
TXS 2241+406	J2244.2+4057	1.171	341.06	40.95	6.3 ± 0.4	3929.90	1.9 ± 1.7
3C 454.3	J2253.9+1609	0.859	343.49	16.15	215.0 ± 1.0	50905.23	261.0 ± 8.0

Table 2: Information on data collection by the MAGIC telescopes.

Association Name	Exposure [h]	Zenith [°]	MJDs-50000	Significance of excess	U.L. (E > 100GeV) 10^{-10} cm^{-2} s^{-1}
TXS 0025+197	5.0	9 to 35	8728 to 8730; 8816 to 8818	0.18	3.07
B2 0234+28	25.6	0 to 36	8379 to 8481	1.63	1.34
AO 0235+164	6.1	11 to 26	7385 to 7398	0.69	1.82
CTA 102	3.2	17 to 42	7715 to 7748; 8105	1.7	5.96
OP 313	13.6	4 to 39	6774 to 6811; 8654 to 8657; 8844 to 8848	-0.5	2.01
4C +55.17	50.0	26 to 42	5512 to 5576; 6671 to 6777	1.5	1.12
3C 454.3	34.6	12 to 48	5505 to 5509; 6815 to 6818	0.6	1.71
TXS 2241+406	29.5	22 to 35	7994; 8665; 8703; 8760; 8805 to 8845 6	0.18	3.07
B2 2234+28A	6.7	1 to 47	8639 to 8677	0.55	3.05

The standard XRTPIPELINE[1] procedure (version 0.13.7) was used while carrying out the X-ray data reduction and calibration. Spectral fitting was performed out using XSPEC (version 12.8.2) [6] in the energy range of 0.2–10 keV and was fitted with a power-law model.

2.5 Sources

Our current work focuses on the FSRQ sources observed by MAGIC but have not resulted in a VHE γ-ray detection. Most of the sources were observed as target of opportunity (ToO) by MAGIC followed by triggering of other MWL observatories. The details of the observed sources are listed in Table 1. Table 2 provides the following information about sources referring to MAGIC observations and analysis: observation time (exposure time), zenith angle range of observation, MJD range (dates of observations), the excess signal calculated using the prescription from [18], and the obtained integral upper limits.

2.6 Results

Table 2 reports the results from the observations and analysis of the nine FSRQ sources. We could not find any statistically significant (> 5σ excess) signal from any of the sources in the sample. The differential U.L.s were calculated in 5 energy bins using MAGIC data in the energy range from 50 GeV to 500 GeV. We assumed the intrinsic spectral index of the γ-ray photon distribution to be α=2.2 for all of sources. The expected VHE flux for each FSRQ is calculated by extrapolation of the *Fermi*-LAT data into the VHE range. We also considered the absorption of γ rays by the EBL using the model used in [12].

[1] https://heasarc.gsfc.nasa.gov/ftools/caldb/help/xrtpipeline.html

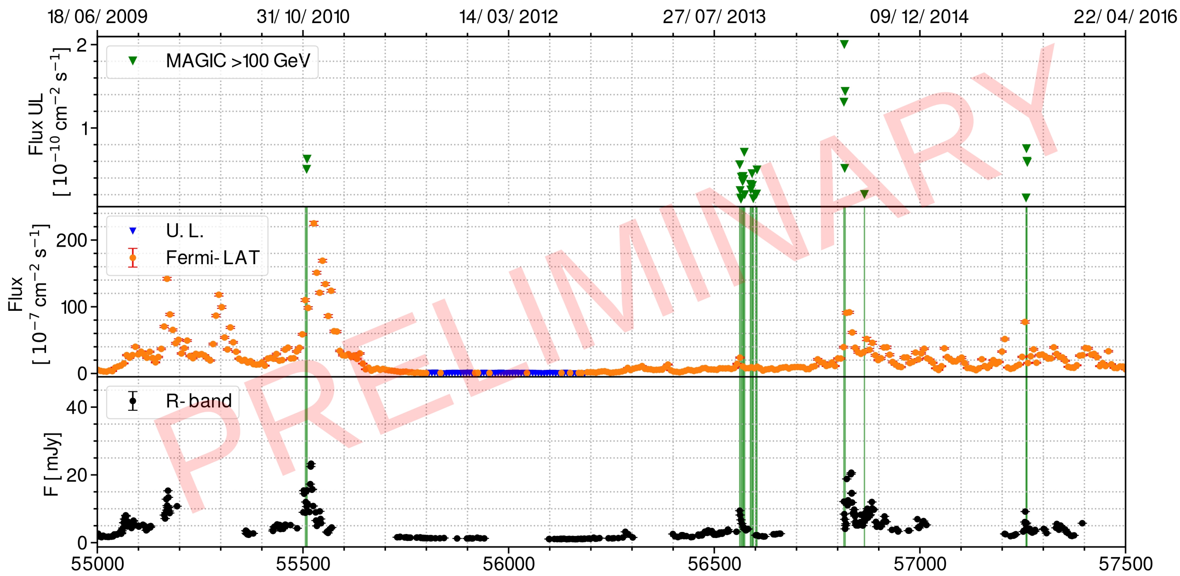

Figure 1: Light curve of 3C 454.3. The green vertical areas indicate the days during which MAGIC observations were carried out.

In Fig. 1 we show the multiwavelength light curve from 3C 454.3, one of the sources from the sample. The green vertical lines show the days during the MAGIC observations.

In Fig. 2 we present the Spectral Energy Distribution of the source 3C 454.3. The U.L. points are close and consistent with the log-parabola model extended from *Fermi*-LAT energy range and with EBL correction.

3. Discussion and conclusions

In our current work we present an archive of U.Ls for nine FSRQs with high redshift distances. We also present other MWL results from observations done in radio, X-ray and HE gamma-rays. These sources were observed by MAGIC telescopes over a decade of time. Most of the observations were carried out following triggers by other multiwavelength observatories in the ToO observations framework of the MAGIC collaboration. For most of the sources the MAGIC U.L. points lay above the log-parabola model extended from the *Fermi*-LAT energy range into the VHE range and with EBL correction.

The lack of detection of significant emission in the VHE range may be due to the short observation time of the MAGIC telescopes when the observations were carried out in the high GeV states of the sources. It may also be due to the fact that there exists a certain delay between the emission enhancement triggering the ToO and the time when observations are started with MAGIC. Additionally, observations and collection of good quality data are also constrained by atmospheric conditions or moonlight.

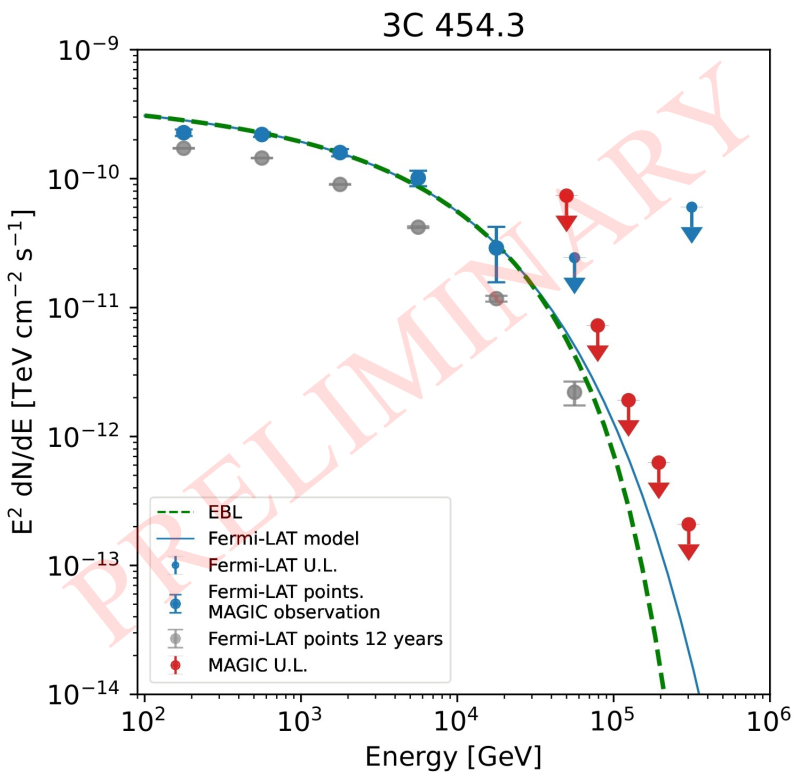

Figure 2: SED in GeV and VHE range for the source 3C 454.3: derived VHE differential upper limits (95 % C.L.) on the flux by MAGIC and *Fermi*-LAT spectrum obtained during the MAGIC observation period

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