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VHE BL Lacs through the MAGIC glasses

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Abstract. In this contribution an overview of the latest results on the study of BL Lac objects with the MAGIC telescopes at the very high energy (VHE, E>100 GeV) gamma-rays is presented. Three new VHE sources were detected during 2014, two BL Lac objects and the gravitational lensed blazar S3 0218+357. MAGIC detected very fast intra-night variability from IC 310. This detection points to smaller emitting regions than the event horizon, this is hard to be explained in the framework of the current theoretical models. The long term multi wavelength (MWL) study of the BL Lac PKS 1424+240 shows correlation between the radio and optical emission, pointing to a common origin. The MWL SED is not well fitted by a one-zone synchrotron-self Compton (SSC) model, but a two-zone SSC model can explain both, the MWL light curve and the SED. Spectral curvature has been found in the observed VHE spectrum from PG 1553+113. This is the first time that spectral curvature compatible with the EBL absorption is found in an individual object.

Keywords. gamma rays: observations, BL Lacertae objects: general

1. The MAGIC telescopes

The MAGIC system consists of two 17 m-diameter Imaging Atmospheric Cherenkov Telescopes (IACT) located on the Roque de los Muchachos, Canary Island of La Palma (28°46′ N,17°53′ W), at a height of 2200 m above see level. MAGIC observes cosmic gamma rays in the energy range between 50 GeV and >10 TeV (known as Very High Energy or VHE band). The system reaches a sensitivity of $(0.66 \pm 0.03)\%$ of the Crab Nebula flux for $E > 220$ GeV in 50 h of observations (Aleksić *et al.* 2014a). The energy threshold (defined as the peak of the energy distribution of triggering gamma rays) of MAGIC is 50 GeV. The system reaches an angular resolution of 0.07° at 300 GeV. The best spectral resolution of 16% is reached at a few hundred GeV.

2. New members of the VHE family

The VHE family is still very limited, and only ∼60 extragalactic emitters have been detected so far. The sample is highly dominated by BL Lacs objects, while there are only four flat spectrum radio quasars (FSRQs). During 2014, three new VHE emitters have been detected with the MAGIC telescopes: the BL Lac objects RBS 0723 (Mirzoyan *et al.* 2014a) and RX J1136.5+6737 (Mirzoyan *et al.* 2014b) and the FSRQ S3 0218+357 (Mirzoyan *et al.* 2014c).

RBS 0723 is a BL Lac object at redshift z=0.198. MAGIC started the observations of the source on 2013 December 3. The data taken between 2014 Jan 1 and Jan 8 (about 10 hours) yields a source detection with a statistical significance of more than 5 standard

deviations (Mirzoyan *et al.* 2014a). The non-detection in the earlier data taken in 2013 Dec. suggests VHE flux variability. The VHE emission measured with MAGIC has a flux of about 2.5% of the Crab nebula at energies above 200 GeV.

RX J1136.5+6737 is a BL Lac object located at z=0.1342. The source was observed with the MAGIC telescopes starting on 2014 January 29. Data taken up to 2014 April 3 (about 20 hours in total) yielded a source detection with a statistical significance of more than 5 standard deviations (Mirzoyan *et al.* 2014b). The averaged flux measured by MAGIC during the 2014 observations corresponded to about 1.5% of the Crab nebula at energies above 200 GeV. RX J1136.5+6737 is an X-ray bright high-peaked frequency BL Lac object as listed in the MAXI 3-year catalog (Hiroi *et al.* 2013). RX J1136.5+6737 has also been detected by Fermi-LAT, in the 2FGL catalog (Nolan *et al.* 2012) with a hard photon index 1.68±0.12, and belongs to the first Fermi-LAT catalog of >10 GeV sources (1FHL; Ackermann *et al.* 2013), showing bright emission above 10 GeV.

S3 0218+357 is a gravitationally lensed blazar located at z=0.94. It is the only system where the gravitational lens effects have been clearly detected in gamma-rays, first detected by *Fermi*-LAT at high energy (HE, E=100 MeV-100 GeV) (Cheung *et al.* 2014). Recently, in July 2014 the source was detected in high state by the *Fermi*-LAT (Buson *et al.* 2014). Due to moon constraints the source could not be observed by MAGIC. However, the observations were scheduled 10 days after the initial flare observed by *Fermi*-LAT, to cover time period in which delayed emission was expected. The source was detected with the MAGIC telescopes during the delayed emission phase between 2014 July 23 to 26 (Mirzoyan *et al.* 2014c). In addition to the interesting study of a gravitational lensed object by first time in the VHE band, this source set a new redshift record in the VHE range which makes S3 0218+357 an ideal target for extragalactic background light (EBL) studies.

3. Short term variability of the active nucleus of IC 310

IC 310 (z = 0.01898) was first classified as a head-tail radio galaxy (Ryle & Windram 1968). However, a more recent analysis of the archival VLBA data of IC 310 shows a blazar-like parsec-scale structure (Kadler *et al.* 2012). The source was detected at high energies above 30 GeV with Fermi-LAT (Neronov *et al.* 2010) as well as at very high energies above 260 GeV with the MAGIC Telescopes (Aleksić *et al.* 2010). IC310 was detected by MAGIC for the first time from October 2009 to February 2010 as part of the Perseus cluster observations. IC 310 is located 0.6° from the cluster center. Since the observations were performed in the so-called wobble mode, i.e. pointing alternatively to two positions 0.4° away (along the RA axis) from the cluster center (NGC 1275), IC 310 was observed off-axis. The position of the source changes from 0.25° to 1° from the camera center in the two wobble positions respectively. The analysis of the closest wobble position detected the source with a flux compatible with a steady emission. However, an improved analysis was carried out using the data from both wobble positions providing more accurate results and resulted in a clear detection of night-to-night variability at confidence level $> 5\sigma$ (Aleksić *et al.* 2014b).

Later on, an exceptionally bright flare of IC 310 was detected in November 2012 reaching a flux level of up to > 0.5 Crab units above 300 GeV during one night (see Fig. 1). Fast intra-night variability was detected during the flare (Aleksić *et al.* 2014c). This is among the fastest variability ever detected in a blazars, together with Mrk 501 (Albert *et al.* 2007) and PKS 2155-304 (Aharonian *et al.* 2007). However, in the later two cases the emission is Doppler-shifted by a larger factor than in IC 310 for which the largest

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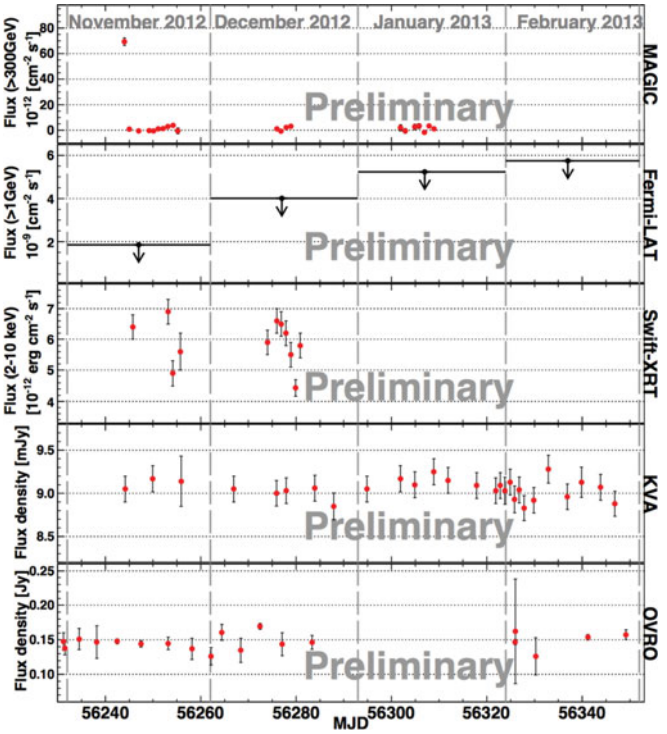

Figure 1. MWL light curve of IC 310: MAGIC above 300 GeV, Fermi-LAT above 1 GeV, Swift-XRT, KVA R-band data and, OVRO at 15 GHz from November 2012 to February 2013. The optical data from KVA presented here are not host-galaxy corrected.

possible Doppler factor is around 6. The intrinsic variability of the source may in fact be so fast that the emission region is smaller than the event horizon light-crossing time.

4. Multiwavelength study of the distant blazar PKS 1424+240

The MAGIC telescopes observed the BL Lac PKS 1424+240 from 2009 to 2011 (Aleksić *et al.* 2014d). Although its redshift is unknown, it is one of the most distant VHE blazars with a redshift lower limit of $z \geqslant 0.6$ (Furniss *et al.* 2013). The differential spectra measured during the different campaigns can be described by steep power laws with the indices ranging from 3.5±1.2 to 5.0±1.7 (Aleksić *et al.* 2014d). The MAGIC spectra corrected for the absorption due to the EBL connect smoothly, within systematic errors, with the mean spectrum in 2009-2011 observed at lower energies by the *Fermi*-LAT. The EBL-corrected MAGIC spectrum is flat with no apparent turn down up to 400 GeV. The MWL light curve shows an increase of the flux in radio and optical bands, and both bands shows correlation in the long term. This could point to a common origin from the same region of the jet, unlike the typical assumption in the canonical one-zone emitting zone where the radio emission is assumed to be produced in a different region of the jet.

The MWL SED shows a two peak distribution with a large separation between the two peaks. The one-zone synchrotron self-Compton (SSC) model requires an extremely high Doppler factor which is much higher than the typical values for blazars. Moreover, as shown in Fig. 2 the one-zone model cannot explain properly the observed spectral shape in optical-UV (after subtraction of the host galaxy). However, a two-component synchrotron self-Compton model describes the SED of the source well with reasonable

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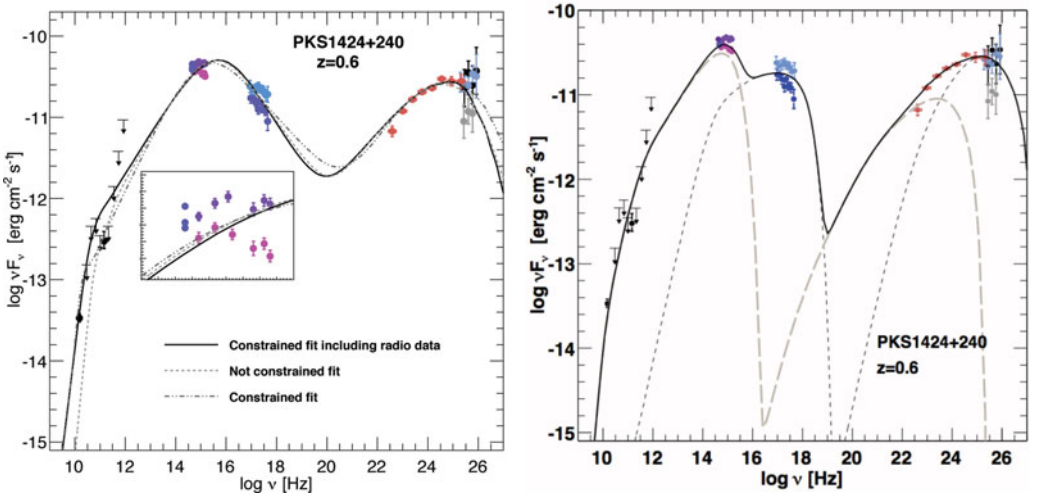

Figure 2. Left panel: SED of PKS 1424+240 fitted with three single-zone SSC models: the high γ_{min} fit (solid line) and the fits that result from the χ^2 minimization (dashed and dot-dashed lines). **Right panel:** SED of PKS 1424+240 fitted with a two-zone SSC model. The long dashed line represents the emission from the outer region and the dashed line from the inner region. In both cases it has been assumed a redshift of z=0.6. Data from radio to VHE: OVRO (black filled circles), Planck (black arrows and filled circle), optical R-band from KVA (blue filled circles), UVOT (pink (lowest state) and purple (highest state) filled circles), Swift-XRT (light blue (high state) and violet (low state) filled circles), *Fermi*-LAT (red filled circles) and MAGIC (2009: black, 2010: gray, 2011: light blue).

Doppler factor parameters, and is in agreement with the observed multi wavelength flux evolution behavior.

5. Probing the VHE spectral curvature

PG 1553+113 is a VHE γ-ray emitter classified as a BL Lac object. Its redshift is constrained by intergalactic absorption lines in the range $0.4 < z < 0.58$ (Danforth *et al.* 2010). The MAGIC telescopes have monitored the source's activity since 2005. In early 2012, PG 1553+113 was found in a high-state, and later, in April of the same year, the source reached its highest VHE flux state detected so far (Aleksić *et al.* 2014e). Simultaneous observations carried out in X-rays during 2012 April show similar flaring behaviour. In contrast, the γ-ray flux at $E < 100$ GeV observed by *Fermi*-LAT is compatible with steady emission.

The VHE spectrum shows clear curvature and a power-law fit can be discarded with confidence level of 4.7σ. Instead, the observed VHE spectrum can be well fitted by either a power-law with an exponential cut-off or by a log-parabola. For the first time spectral curvature compatible with the EBL imprint (according to the present generation of EBL models) was found in an individual source (Fig. 3).

New constraints on the redshift were derived from the VHE spectrum. These constraints are compatible with previous limits and suggest that the source is most likely located around the optical lower limit, $z = 0.4$, based on the detection of Lyα absorption (Danforth *et al.* 2010). The MWL SED during the flaring episode is well described by a one-zone SSC model.

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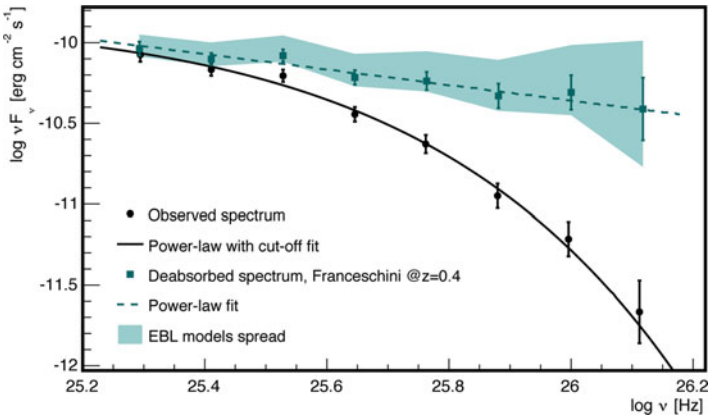

Figure 3. SED of PG 1553+113 as measured by MAGIC during the flare state of 2012 April. The observed SED is shown as black circles, and the black solid line represents the best fit to a power-law with an exponential cut-off. The absorption-corrected spectrum assuming z = 0.4 and using the EBL model by Franceschini *et al.* (2008) is shown by the green squares; the dashed green line is the best-fitting power-law. The green shaded area account for the uncertainties derived by the use of different EBL models (Domínguez *et al.* 2011; Kneiske & Dole 2010; Franceschini *et al.* 2008; Gilmore *et al.* 2012).

6. Summary

The MAGIC telescopes detected recently in 2014 July the first gravitational lensed blazar S3 0218+357 in the VHE band. Also two new BL Lac objects has been detected during 2014.

Fast intra-night variability have been found in IC 310. Due to its low Doppler factor with respect to the typical blazars, it points to emitting regions which are smaller than the event horizon being therefore difficult to be explained by the current models.

The long term MWL study of the BL Lac PKS 1424+240 shows correlation between the radio and optical flux and points to a common origin. The MWL observations also challenge the standard one-zone SSC model, and a two-zone model is found to describe the SED.

Spectral curvature was found in the observed VHE spectrum from the BL Lac PG 1553+113. For the first time spectral curvature compatible with the EBL imprints was found in an individual target.

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