

## Latest MAGIC discoveries pushing redshift boundaries in VHE Astrophysics

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## Latest MAGIC discoveries pushing redshift boundaries in VHE Astrophysics

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### Abstract.

The search for detection of  $\gamma$ -rays from distant AGNs by Imaging Atmospheric Cherenkov Telescopes (IACTs) is challenging at high redshifts, not only because of lower flux due to the distance of the source, but also due to the consequent absorption of  $\gamma$ -rays by the extragalactic background light (EBL). Before the MAGIC discoveries reported in this work, the farthest source ever detected in the VHE domain was the blazar PKS 1424+240, at  $z > 0.6$ . MAGIC, a system of two 17 m of diameter IACTs located in the Canary island of La Palma, has been able to go beyond that limit and push the boundaries for VHE detection to redshifts  $z \sim 1$ . The two sources detected and analyzed, the blazar QSO B0218+357 and the FSRQ PKS 1441+25 are located at redshift  $z = 0.944$  and  $z = 0.939$  respectively. QSO B0218+357 is also the first gravitational lensed blazar ever detected in VHE. The activity, triggered by *Fermi*-LAT in high energy  $\gamma$ -rays, was followed up by other instruments, such as the KVA telescope in the optical band and the *Swift*-XRT in X-rays. In the present work we show results on MAGIC analysis on QSO B0218+357 and PKS 1441+25 together with multiwavelength lightcurves. The collected dataset allowed us to test for the first time the present generation of EBL models at such distances.



## 1. Introduction

The Very High Energy (VHE,  $>100\text{GeV}$ ) sky is populated by almost 60 blazars, active galactic nuclei which relativistic jet is pointing in the direction of the Earth. The peculiar orientation of the jet towards the observer, and their features such as continuum emission, rapid variability, high polarization, and radio structures dominated by compact radio cores, make them a perfect laboratory to study the nature of the emission at different wavelengths, from radio up to the TeV range, and to investigate, at the highest energies, the effect of the EBL absorption on the  $\gamma$ -rays produced by the central engine of the galaxy. Until recently, the farthest blazar detected at VHEs was PKS 1424+240, at  $z > 0.6$  [1]. Thanks to the recent discoveries in VHE by MAGIC of QSO B0218+357 [2] and PKS 1441+25 [3], at respectively  $z = 0.944$  [4] and  $z = 0.939$ <sup>1</sup> the VHE sky suddenly expanded to its limits reaching the unprecedented redshift  $z \sim 1$ . Beyond the so-called cosmic  $\gamma$ -ray horizon, the Universe becomes opaque to VHE  $\gamma$ -ray radiation due to the interaction of high energy  $\gamma$ -rays with the diffuse EBL, producing electron-positron pairs. At the redshift of  $z \sim 1$  this absorption results in a cut-off at the energy of  $\sim 100\text{ GeV}$  [6, 7]. Such energies are at the lower edge of the performance of the current generation of Imaging Atmospheric Cherenkov Telescopes (IACTs), and only a low threshold of the instrument can make the detection and the consequent study of the source possible. To maximize the detection chance, the observations are often triggered by a high state observed in lower energy ranges. The Large Area Telescope on board *Fermi*, scanning the whole sky in the High Energy (HE,  $0.1\text{ GeV} < E < 100\text{ GeV}$ ) range provides alerts of high energy fluxes and spectral shape triggering MAGIC observations, as for the two sources we are describing in this work.

## 2. Instruments in brief

MAGIC is a stereoscopic system consisting of two 17m diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatorio del Roque de los Muchachos, on the Canary Island of La Palma. The current integral sensitivity for low-zenith observations ( $z_d < 30^\circ$ ) above 100 GeV is  $1.445 \pm 0.015\%$  of the Crab Nebula's flux in 50 h, while the one above 220 GeV is  $0.66 \pm 0.03\%$ . The Field of View (FoV) of MAGIC is  $3.5^\circ$  [8]. The Large Area Telescope (LAT) on board of *Fermi* is an imaging high-energy  $\gamma$ -ray telescope in the energy range from about 20 MeV to more than 300 GeV [9]. The LAT's FoV covers about 20% of the sky at any time, and it scans continuously, covering the whole sky every three hours. For both sources, multiwavelength (MWL) observations were performed, collecting data from other instruments. *Swift*-XRT [10] in the X-ray and KVA<sup>2</sup> in the R-band were collected for QSO B0218+357 and PKS 1441+25 while for PKS 1441+25 only, data from NuSTAR [11] in Hard X-ray, *Swift*-UVOT [12] in optical-UV, Hans-Haffner<sup>3</sup> in the optical R-band, CANICA<sup>4</sup> in the Near Infrared and Metsähovi for Radio were used [13].

## 3. Observations and Results

### 3.1. QSO B0218+357

QSO B0218+357 is a blazar located at the redshift of 0.944 [4]. The object is gravitationally lensed by a galaxy [PBK93] B0218+357 G located at  $z = 0.68$ . The time delay between the two flares, measured by *Fermi*-LAT during a previous flare in 2012, was expected to be  $11.46 \pm 0.16$  days. In July 2014 a flare observed by *Fermi*-LAT [14] triggered follow-up observations of the MAGIC telescopes which in turn led to the discovery of VHE  $\gamma$ -ray emission from QSO B0218+357 [2] from the secondary component of the flare, observed at the expected

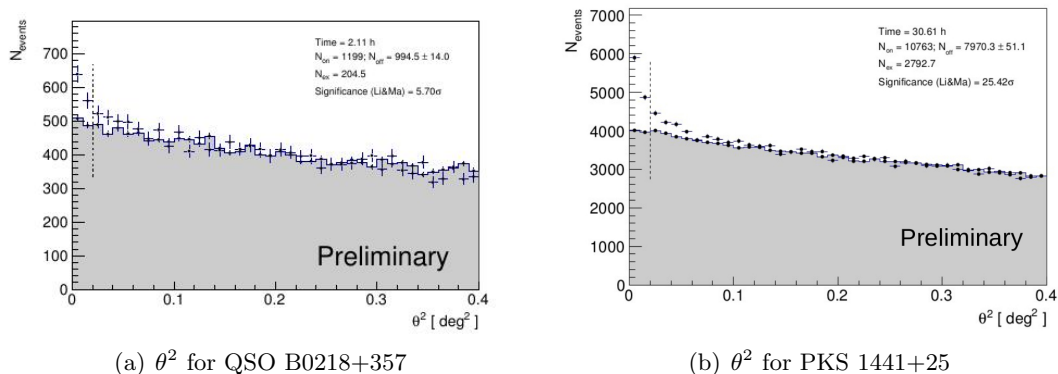
<sup>1</sup> From SDSS: <http://skyserver.sdss.org/dr10/en/get/SpecById.ashx?id=6780257851631206400> and [5]

<sup>2</sup> <http://users.utu.fi/kani/1m>

<sup>3</sup> <http://schuelerlabor-wuerzburg.de/?p=Sternwarte>

<sup>4</sup> <http://www.inaoep.mx/~astrofi/cananea/canica/>

time of arrival with a significance of  $5.7\sigma$  (see Fig.1, panel a). As in the case of PKS 1441+25 the analysis of the data, performed within the standard MAGIC analysis framework *MARS* [8, 15] was carried on with the aim of ad-hoc Monte Carlo (MC) simulations to match the night-sky background. The observations were performed in 14 nights in July and August 2014 for a total duration of 12.8 h at intermediate zenith angle ( $20^\circ < zd < 43^\circ$ ).



**Figure 1.** Distribution of the squared angular distance  $\theta^2$  between the reconstructed source position and the nominal source position (points) or the background estimation position (shaded area) for QSO B0218+357 (a) and PKS 1441+25 (b). Vertical dashed line shows the value of  $\theta^2$  up to which the number of excess events and significance are computed.

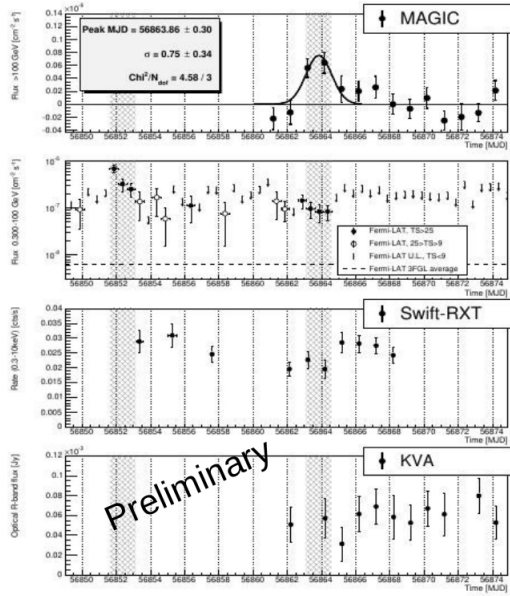
The preliminary MWL lightcurve of the source is shown in Fig.2. The light curve obtained by MAGIC above 100 GeV is compared with the emission observed above 0.3 GeV by *Fermi*-LAT, *Swift*-XRT in 0.3-10 keV range and in the bottom panel by KVA in the R-band. The *Fermi*-LAT emission during the second component of the flare was a factor 20 higher than the average state of the source [16]. During both components of the flare the photon index was significantly harder [17] than the average one. The MAGIC emission occurred at the same time as the delayed, weaker component of the flare in *Fermi*-LAT. The two flaring nights give the mean flux of  $(5.8 \pm 1.6_{stat} \pm 2.4_{syst}) \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$  above 100 GeV [18].

The spectral features of the emission, modelling and impact on the EBL measurements will be discussed in [19].

### 3.2. PKS 1441+25

The MAGIC telescopes monitored PKS 1441+25 in April and May 2015 for a total of  $\sim 30$  h. The observations were performed in the standard wobble mode with a  $0.4^\circ$  offset and four symmetric positions with respect to the camera center. The data were collected in the zenith angle range of  $3^\circ < zd < 38^\circ$ . The analysis of the data was performed using the standard MAGIC analysis framework *MARS* [8, 15] and, as in the case of QSO B0218+357, with Monte Carlo simulations matching the night-sky background levels. PKS 1441+25 was detected with a significance of  $25.5\sigma$ , see Fig.1, panel b.

The MWL lightcurve for PKS 1441+25 is shown in Fig.3. The differential VHE spectrum was measured from 40 to 250 GeV. Employing state-of-the-art EBL models, upper limits to the EBL density are derived and reported in [20]: the upper limits on the optical depth ( $\tau$ ) calculated under the assumption of an intrinsic spectrum compatible with a power-law function result in  $\tau(E) < 1.73\tau_{D11}$ , where  $\tau_{D11}$  is the optical depth at  $z = 0.939$  from the Dominguez et al. (2011) model [21].



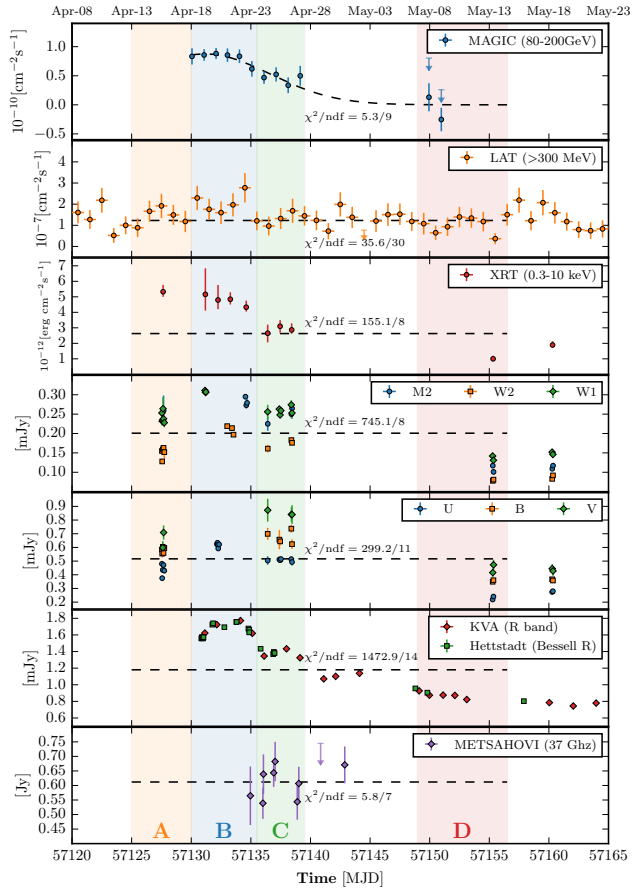
**Figure 2.** MWL for QSO B0218+357, during the flaring state in July/August 2014. Top panel: MAGIC (points) above 100 GeV and Gaussian fit to the peak position (thick solid line). Second panel from the top: *Fermi*-LAT above 0.3 GeV (note the log scale) with the average flux from the 3rd *Fermi* Catalog [16] marked with dashed line. Third panel from the top: *Swift*-XRT in 0.3-10 keV range from the automatic analysis [22]. Bottom panel: KVA in R band.

#### 4. Conclusions

QSO B0218+357 ( $z = 0.944$ ) and PKS 1441+25 ( $z = 0.939$ ) were detected for the first time in the VHE range by MAGIC, extending the maximum redshift for VHE  $\gamma$ -ray observations up to a distance  $z \sim 1$ , near the cosmic  $\gamma$ -ray horizon. QSO B0218+357 was the first ever gravitationally lensed blazar detected in the VHE, and the analysis for this peculiar source is still ongoing [19]. The EBL was probed and investigated, obtaining constraints on the existing models for PKS 1441+25. The reduction in the  $\gamma$ -ray detection threshold operated by MAGIC during the last years thanks to several upgrades and to the improvement of the performance also from the analysis point of view led to the discovery of such distant galaxies and opens the door to the possibility to detect even farther sources at VHE and improve the present knowledge of the  $\gamma$ -ray Universe.

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**Figure 3.** MWL lightcurve for PKS 1441+25. The shaded areas marked as A, B, C, D depict four different states of the source as in [20].

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