

## Article

# Broad Band Observations Of Gravitationally Lensed Blazar QSO B0218+357 During A Gamma-Ray Outburst

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**Abstract:** QSO B0218+357 is a blazar located at a cosmological redshift of 0.944. The source is gravitationally lensed by a spiral galaxy located at the redshift of 0.68. Strong gravitational lensing splits the signals emitted by the source into two components separated by 10–12 days, as observed in radio and gamma-ray bands. In July 2014 a GeV flare was observed by *Fermi*-LAT, triggering follow-up observations with the MAGIC telescopes at energies above 100 GeV. The expected time delay between the components allowed us to plan broad band MWL observations before, during and after the trailing component of the emission. The MAGIC observations at the expected time of arrival of the trailing component resulted in the first detection of QSO B0218+357 in Very-High-Energy (VHE, >100 GeV) gamma rays. It is both the farthest known VHE object and one of only a few Flat Spectrum Radio Quasars detected in this energy range. We report here the observed multiwavelength spectral and temporal properties of the emission during the 2014 flare.

**Keywords:** Gamma rays; galaxies; Gravitational lensing: strong; Galaxies: jets; Radiation mechanisms: non-thermal; Galaxies: individual: QSO B0218+357

## 1. Introduction

Most of the blazars detected in the VHE range are relatively close-by sources with redshift  $z \lesssim 0.5$ . With the recent detection by the MAGIC (Major Atmospheric Gamma Imaging Cherenkov) telescopes of VHE gamma-ray emission from two sources at the redshift  $z \sim 0.94$ : QSO B0218+357 [1] and PKS1441+25 [2], the boundaries of the known gamma-ray universe nearly doubled. Observations of distant sources in VHE gamma-rays are strongly affected by an absorption in the extragalactic background light (EBL). At a redshift of QSO B0218+357 it results in a cut-off at energies  $\sim 100$  GeV, which is the lower edge of the sensitivity range of the current generation of Imaging Atmospheric Cherenkov Telescopes.

QSO B0218+357 is classified as a flat spectrum radio quasar (FSRQ) [3]. Its redshift has been estimated on  $z = 0.944 \pm 0.002$  [4], the estimation is however based on only a single line [5]. The object is gravitationally lensed by the face-on spiral galaxy [PBK93] B0218+357 G. Strong gravitational lensing by a spiral galaxy [PBK93] B0218+357 G produces two distinct images of QSO B0218+357 visible in radio and optical frequencies [6]. Variability of the two radio components allowed a measurement of a delay of 10-12 days between the leading and trailing image [7–10]. The leading component of QSO B0218+357 (often called image A in literature) is located at a smaller right ascension value than the trailing component (image B). The former shows a  $\sim 3.6$  times larger flux in radio frequencies [8], but in the optical range is strongly absorbed [11].

QSO B0218+357 went through a gamma-ray high state in 2012. A series of individual outbursts was registered by the *Fermi*-LAT [12], which however does not have the necessary angular resolution to spatially disentangle the two emission components. Nevertheless, the statistical analysis of the light curve auto-correlation function led to a measurement of the time delay between them of  $11.46 \pm 0.16$  days. The average magnification factor, contrary to radio measurements, was estimated to be  $\sim 1$ .

A new gamma-ray flare of QSO B0218+357 was observed by *Fermi*-LAT in July 2014 [13]. The magnification ratio of both images in this case was similar to the one observed in radio frequencies [14]. The MAGIC follow-up observations led to the discovery of VHE gamma-ray emission from QSO B0218+357 [1]. In this work we present the results of optical, X-ray and gamma-ray observations of QSO B0218+357 during the flaring state in July 2014.

## 2. Observations and data analysis

The VHE gamma-ray observations of QSO B0218+357 were performed with the MAGIC telescopes. At GeV energies the source was monitored by *Fermi*-LAT, in X-ray by *Swift*-XRT and in optical by KVA. Note that angular resolution of all the above instruments is insufficient for spatially resolving the emission from the two lensed image components of QSO B0218+357, hence a sum of the leading and trailing image is observed.

MAGIC is a system of two 17 m Cherenkov telescopes located in the Canary Island of La Palma at a height of 2200 m a.s.l. [15]. The large mirror dish of MAGIC telescopes allowing us to observe gamma rays with energies as low as  $\sim 50$  GeV [16]. The telescopes could not follow immediately the 2014 flare from QSO B0218+357 revealed by *Fermi*-LAT as it occurred during the full Moon time. The MAGIC observations were scheduled starting from the 23<sup>rd</sup> of July (MJD=56861, two nights before the expected delayed emission) and lasted for 14 consecutive nights. The total exposure time was 12.8 h and the source was seen in the zenith angle  $20^\circ - 43^\circ$ . The data reduction (stereo reconstruction, gamma/hadron separation and estimation of the energy and arrival direction of the primary particle) was performed using MARS, the standard analysis software of MAGIC [16,17].

*Fermi*-LAT is a pair-conversion telescope optimized for energy range 20 MeV to 300 GeV [18]. The instrument is normally operated in scanning mode, providing coverage of the full sky every three hours, however between December 2013 and December 2014, an observation strategy emphasizing coverage of the Galactic center region was used. The coverage on the QSO B0218+357 position was on average a factor of 0.6. Additionally, at the time of the expected delayed emission, *Fermi*-LAT performed a 2.7 days long Target of Opportunity observation on QSO B0218+357 to enhance exposure towards the source position. *Fermi*-LAT data were extracted from a circular region of interest (ROI) of  $15^\circ$  radius centered at the QSO B0218+357 radio position. The analysis was done in the energy range  $0.1 - 300$  GeV using the standard *Fermi Science Tools* (version v9r34p1) in combination with the P7REP\_SOURCE\_V15 LAT Instrument Response Functions. The used data span time period between MJD 56849–56875 (2014 July 11<sup>th</sup> – August 8<sup>th</sup>). We applied the `gtmktime` filter (#3) cuts to the

LAT data<sup>1</sup>. Time intervals when the LAT boresight was rocked with respect to the local zenith by more than  $52^\circ$  and events with zenith angle  $> 100^\circ$  were excluded to limit the contamination from Earth limb photons. The spectral model of the region included all sources located within the ROI with the spectral shapes and the initial parameters for the modeling set to those reported in the third *Fermi*-LAT source catalog, 3FGL [19]. `iso_source_v05.txt` and `gll_iem_v05.fit` have been used as the isotropic and Galactic diffuse background components. To obtain the light curve the QSO B0218+357 was modeled with a power-law spectral shape with normalization and index free to vary. To evaluate the significance of the detection we used the Test Statistic (TS) value defined as  $-2\log(L_0/L)$ , where  $L_0$  is the maximum likelihood value for a model without an additional source (the 'null hypothesis') and  $L$  is the maximum likelihood value for a model with the additional source at the location of QSO B0218+357. Flux upper limits at the 95% confidence level were calculated for time intervals where TS was  $< 9$ .

The *Swift* X-ray Telescope (XRT, [20]) is a CCD imaging spectrometer, sensitive in the 0.2-10 keV band. QSO B0218+357 was observed by the *Swift* satellite during 10 epochs, each with an exposure of about 4.5 ks. The observations first followed the original alert of enhanced activity in GeV gamma rays, and then were resumed at the expected time of arrival of the trailing flare. The data were reduced with the HEASoft package version 6.17, using the calibration files available in the version 20140709 of the *Swift*-XRT CALDB. We run the task `xrtpipeline` with standard screening criteria on the observations performed in pointing mode. Observations were done in Photon Counting (PC) mode with count rates about 0.02 counts/s. The source and background counts were extracted with the task `xrtproducts` from a circular region of 35" for the source and 120" for the background.

The observations in the optical R-band were performed using the 35 cm Celestron telescope attached to the KVA 60 cm telescope, located close to the MAGIC telescopes site. QSO B0218+357 was observed between 2014, July 24 (MJD 56862.2) and 2014, August 5 (MJD 56874.2) on almost nightly basis. The data has been analyzed using the semi-automatic pipeline developed at the Tuorla Observatory (Nilsson et al. 2016, in prep.). The magnitudes are measured using differential photometry. The absolute calibration of the optical fluxes was done using stars with known magnitudes present in the field of view of the instrument during observations of all targets of a given night (see Table 3 of [21] and references therein). As QSO B0218+357 is rather faint in the optical range and the telescope is relatively small, several images from the same night were combined for the measurement of the average flux.

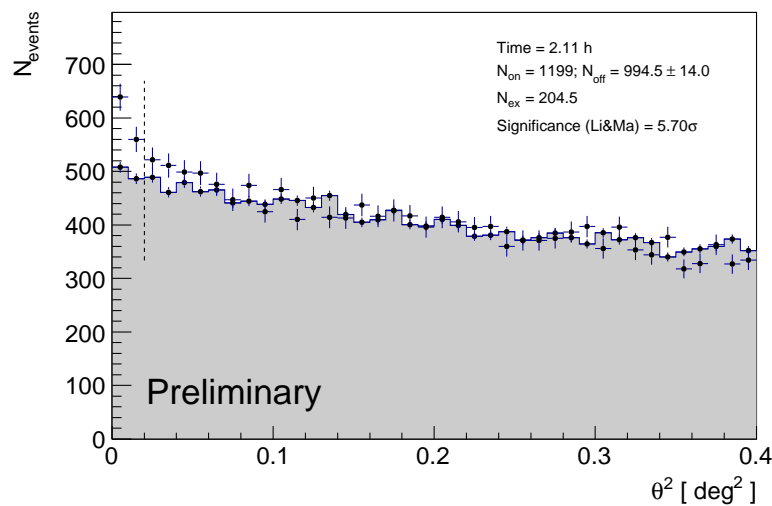
### 3. Results

The VHE gamma-ray emission was detected by the MAGIC telescopes on the nights of 25<sup>th</sup> and 26<sup>th</sup> of July 2014 (MJD of 56863.2 and 56864.2 respectively), during the expected time of arrival of trailing component of the flare registered by *Fermi*-LAT. The detection cuts were optimized to provide the best sensitivity in the 60-100 GeV estimated energy range (see [16]). The total observation time of 2.11 hr during those 2 nights yielded a statistical significance of  $5.7\sigma$  (see Fig. 1).

The multiwavelength light curve of QSO B0218+357 is shown in Fig. 2. A fit to the MAGIC light curve above 100 GeV (Fig. 2, a) with a Gaussian function gives the peak position at MJD of  $56863.86 \pm 0.30_{\text{stat}}$  and the standard deviation of  $0.75 \pm 0.34_{\text{stat}}$  days. The mean flux of the two flaring nights is  $(5.8 \pm 1.6_{\text{stat}} \pm 2.4_{\text{syst}}) \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$ . The relatively large systematic error is a result mainly of a 15% uncertainty in the energy scale.

The GeV light curve of QSO B0218+357 measured by *Fermi*-LAT is shown in panel b) of Fig. 2. Significant GeV gamma-ray emission was detected both during the leading flare and the expected

<sup>1</sup> see [http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone\\_Likelihood/Exposure.html](http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Likelihood/Exposure.html)



**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). Vertical dashed line shows the value of  $\theta^2$  cut, up to which the number of excess events and significance are computed.

arrival time of the trailing component (TS of 615 and 129 respectively). The flux above 0.1 GeV during the two nights of MAGIC detection is  $F_{>0.1\text{GeV}} = (1.7 \pm 0.4) \times 10^{-7} \text{cm}^{-2} \text{s}^{-1}$ .

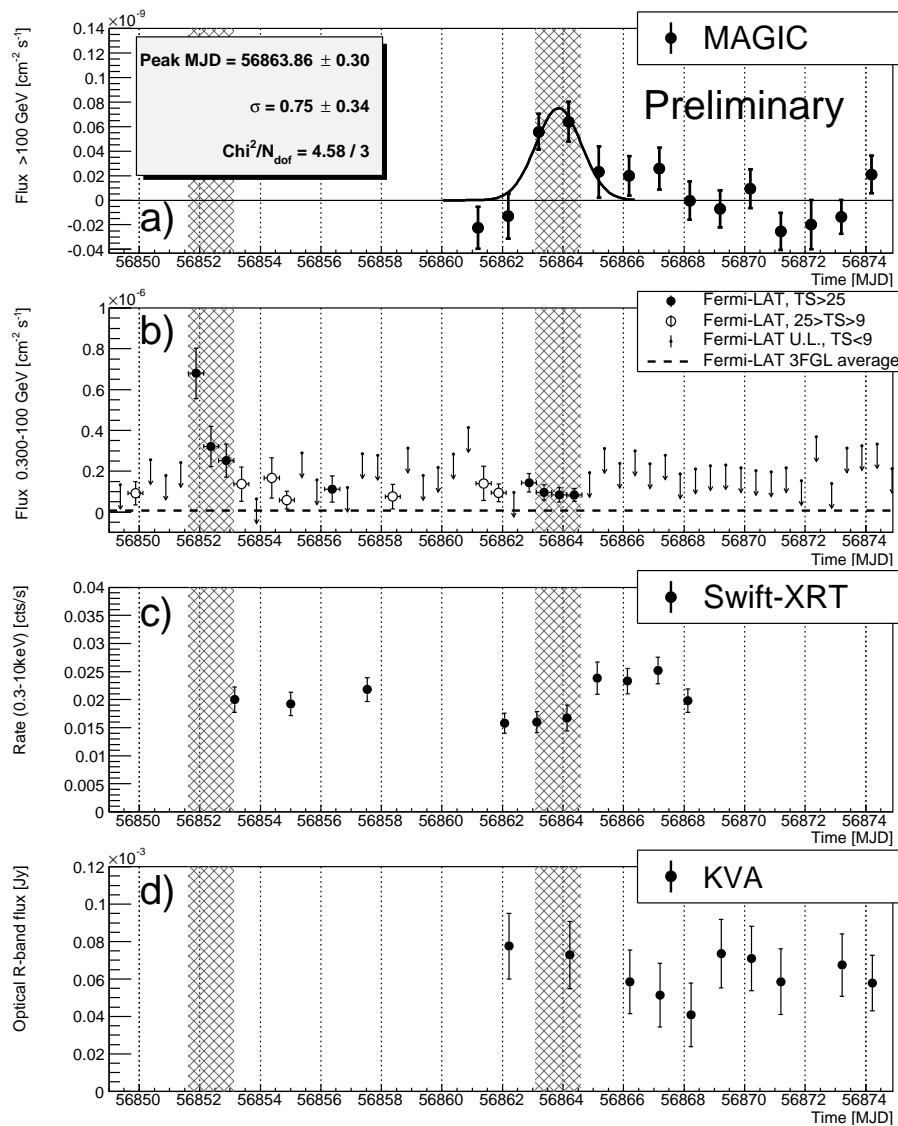
In the panel c) of Fig. 2 we show the X-ray light curve of QSO B0218+357. There is only a small hint of variability in the investigated time span. A constant fit gives  $\chi^2/N_{\text{dof}} = 21.3/9$ , corresponding to the probability of 1.1%. Moreover, the source did not show an enhanced flux in the X-ray range during the trailing gamma-ray flare.

The optical light curve of QSO B0218+357 in the R band is shown in the panel d) of Fig. 2. In all of our observations the source was fainter than 19 magnitudes. The resulting error bars for the flux points were therefore relatively large and no significant variability was detected.

#### 4. Discussion

MAGIC has detected VHE gamma-ray emission from QSO B0218+357 during the expected time of arrival of the trailing component of a flare in July 2014. It is currently the most distant source detected with a ground-based gamma-ray telescope. The strong gravitational lensing effect with a measured at lower frequencies delay between individual components allowed to plan the MAGIC observations before and during the flare. The VHE gamma-ray emission lasted for two nights, similarly like the leading component seen clearly by *Fermi*-LAT. Interestingly, the gamma-ray flare seen by MAGIC was not accompanied with a similar increase in either optical or in X-ray flux. This is unusual for FSRQs, where often a correlation is seen. Lack of correlation in the case of QSO B0218+357 flare might be explained by a two-zone scenario, with one zone predominately responsible for the low energy emission, and gamma rays being produced mainly in the second zone. The detailed modelling of MWL emission with a two-zone model will be presented in Ahnen et al. in prep.

Moreover, huge opacity for gamma rays occurs in the innermost regions of a FSRQ. Therefore, observations of gamma rays with energies above 100 GeV by the MAGIC telescopes can constrain the location of the second emission zone. In order to avoid the strong absorption the gamma-rays should have been produced close to or beyond the BLR radius (see e.g. [22] and references therein). The second region must be also sufficiently small to allow day time variability observed in gamma-rays, namely  $R \lesssim D\tau c/(1+z) = 2.7 \times 10^{16}(D/20)(\tau/1\text{d})[\text{cm}]$ , where  $R$  is the radius of the source region,  $D$  is the Doppler factor,  $\tau$  is the observed variability time scale and  $c$  is the speed of light. The



**Figure 2.** Multiwavelength light curve of QSO B0218+357 during the flaring state in July/August 2014. a) MAGIC (points) above 100 GeV with a Gaussian fit to the peak position (thick solid line). b) *Fermi*-LAT above 0.3 GeV with the average flux from the 3rd Fermi Catalog [19] showed as a dashed line. Notice that during the days where the trailing emission was expected *Fermi*-LAT was in pointing mode allowing to significantly detect lower flux levels. c) *Swift*-XRT count rate in the 0.3-10 keV range. d) KVA in R band (not corrected for the contribution of host/lens galaxies and the Galactic extinction). The two shaded regions are separated by 11.46 days.

quasi-stable optical and X-ray emission might however originate from both a larger and a more inner region of QSO B0218+357.

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**Author Contributions:** JS, JBG, MM and MN analyzed the MAGIC data. SB and JBG analyzed the *Fermi*-LAT data. AS and MN analyzed the *Swift*-XRT data. KN analyzed the KVA data. JS coordinated the project and led writing of the manuscript. All the coauthors participated in discussion of obtained results.

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