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Multiwavelength monitoring of the gravitationally lensed blazar QSO B0218+357 between 2016 and 2020

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QSO B0218+357 is currently the only gravitationally lensed source from which very-high-energy (VHE, $\gtrsim$100GeV) gamma-ray emission has been detected. We report the multiwavelength monitoring observations of this source performed between 2016 and 2020 in radio interferometry, optical, X-ray and gamma-ray bands. During the monitoring individual flares and hints of enhanced states in optical, X-ray and GeV bands have been observed, and the simultaneous data taken by the MAGIC telescopes allow us to search for the VHE gamma-ray emission associated with these events.

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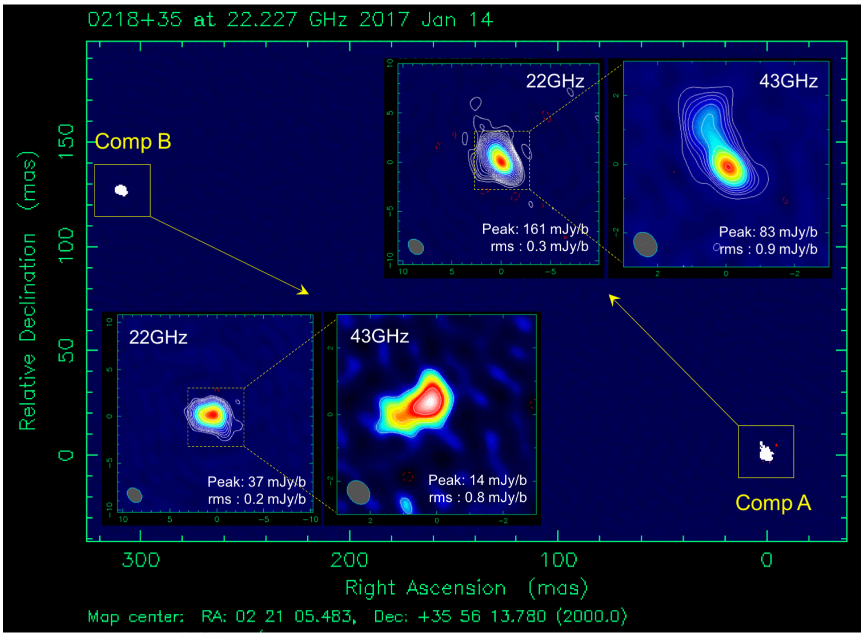

Figure 1: KaVA radio view of the source. The radio interferometry zoom to the two image components A and B is shown in inset panels.

1. Introduction

QSO B0218+357is a Flat Spectrum Radio Quasar (FSRQ) located at a redshift of $z_s = 0.944 \pm 0.002$ [1]. Only a few of such objects has been detected in the very-high-energy (VHE, $\gtrsim 100\,\mathrm{GeV}$) gamma-ray band. Triggered by a gamma-ray flare observed by *Fermi*-LAT the MAGIC telescopes performed follow-up observations which led to the discovery of VHE gamma-ray emission from QSO B0218+357 [2].

QSO B0218+357 is gravitationally lensed by B0218+357 G, an intervening galaxy at a redshift of $z_l = 0.68466 \pm 0.00004$ [3]. Strong gravitational lensing produces multiple images of the original source, which are affected by individual magnifications of the observed flux. Different geometrical paths and gravitational delay cause the observed radiation from different images to arrive at different times to the observer. Radio observations of QSO B0218+357 reveal two images A and B separated by only 335 mas and an Einstein ring of a similar size [4]. The A component (located westwards) is brighter and also arrives earlier compared to B (see Fig. 1).

Variable radio emission in 5-15 GHz bands led to measurements of time delays between the two components in range of 10-12 days (see e.g. [5–7]). While the individual images cannot be resolved at GeV energies, statistical analysis of the 2012 high-state *Fermi*-LAT light curve auto-correlation function allowed a measurement of a time delay with a similar value (11.46 ± 0.16 d, [8]). At radio frequencies the ratio of the fluxes of A and B components is 3.57-3.73 [6]. However the observed magnifications can be affected by absorption and microlensing effects. Unfortunately, since the detection of the VHE gamma-ray emission in 2014 only covered the time of the B image of the flare no measurement of magnification ratio or delay could be performed at VHE gamma-ray energies.

FSRQ are known to experience short-duration flares. Also in the case of QSO B0218+357 the

VHE gamma-ray emission observed in 2014 lasted only two nights. Such time scale is comparable in duration with the *Fermi*-LAT 24 hr data acquisition, transfer and analysis time. Therefore, the shortness of the VHE gamma-ray flare significantly hinders the possibility of Target of Opportunity observations of a flare in the earlier image. Thus, since 2016 a different strategy has been employed by the MAGIC Collaboration. Monitoring has been performed only in time slots that, in case a flare is detected, would result also in visibility in dark-time conditions at zenith $\lesssim 30^\circ$ after 11 days (i.e. when the second component is expected). During monitoring slots MAGIC observations were performed, and contemporaneous multiwavelength (MWL) coverage from radio to GeV gamma-rays was assured. In here we report the preliminary results of this broadband monitoring. The final results will be shown in [9].

2. Observations and data analysis

During 2016-2020 monitoring campaign QSO B0218+357 was observed over a broad energy range: radio (OVRO and KaVA interferometry), optical-UV (KVA and NOT; *Swift*-UVOT and *XMM*-OM), X-ray (*Swift*-XRT and *XMM*-Newton), GeV gamma rays (*Fermi*-LAT) and VHE gamma rays (MAGIC).

MAGIC is a system of two imaging atmospheric Cherenkov telescopes with a mirror dish diameter of 17 m each, located in the Canary Islands, on La Palma [10]. The data were analyzed using the standard analysis package of MAGIC, MARS [11]. The source has been monitored with the MAGIC telescopes according to the above-mentioned scheme between MJD 57397 and 58875 in dark night conditions. To optimize exposures, in the slots allowed for visibility conditions every second night was scheduled (as long as it was allowed by the weather conditions or scheduling conflicts). The data set consists of 72.7 hr of good quality data, spread over 73 nights. The second half of the dataset (since MJD 58122) has been taken with the novel Sum-Trigger-II [12]. That part of the dataset was analyzed with a dedicated low-energy analysis procedures including a special image cleaning [13, 14].

The Large Area Telescope (LAT) is a pair conversion detector located on board of *Fermi* Gamma-ray Space Telescope. It scans the whole sky every three hours in the energy range between a few tens of MeV and few TeV [15]. We selected the *Fermi*-LAT data taken between MJD 56929 and 58876 in the energy range 100 MeV - 2 TeV in a region of interest of 15°. The data were processed using the Fermitools version 1.2.23 and Fermipy [16] version 0.19.0, with instrument response function P8R3_SOURCE_V2.

XMM-Newton [17] has observed the source four times between August 2019 to January 2020. The data were processed using the *XMM*-Newton Science Analysis System [SAS v.18.0.0, 18]

The X-ray Telescope [XRT, 19] on-board the *Neil Gehrels Swift observatory (Swift)* observed the source four times between January 2016 and January 2020. The data were processed using the standard data analysis procedure [20], using the configuration described by [21]. Simultaneously with X-ray data, *u* band UV data have been taken with *Swift*-UVOT [22] and *XMM*-OM.

In optical range the source has been monitored by two ground based instruments: Nordic Optical telescope (NOT) and 35 cm Celestron telescope attached to the Kunliga Vetenskapsakademi (KVA) telescope. The data were analyzed using the semi-automatic pipeline and standard procedures of differential photometry [23].

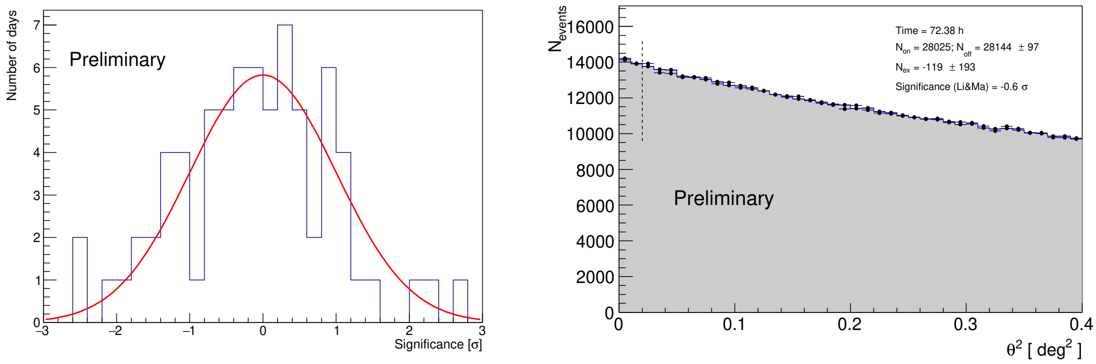

Figure 2: Left panel: distribution of significances of individual nights of MAGIC observations, for reference the red line shows a Gaussian distribution with a mean of 0 and standard deviation of 1. Right panel: Distribution of the squared angular distance between the nominal and reconstructed position of QSO B0218+357 (points) and corresponding background estimation (shaded region).

In radio range QSO B0218+357 was observed with KaVA at 22 and 43 GHz, a joint VLBI array of KVN (Korean VLBI Network) and VERA (VLBI Exploration of Radio Astrometry). The observations were performed in 16 sessions spreading between January 2017 and January 2019. The initial data calibration was performed using the National Radio Astronomy Observatory Astronomical Image Processing System (AIPS, [24]) based on the standard KaVA/VLBI data reduction procedures [25]. Imaging was performed in the Difmap software [26]. The source is also one of the monitored sources with the Owens Valley Radio Observatory (OVRO) 40-Meter Telescope. The observations and data reduction is described in detail in [27]. While in KaVA observations the emission from the two images of the source can be easily disentangled, single dish OVRO measures total flux densities integrated over the whole lensed structures: A, B and the Einstein ring.

3. Results

Due to expected variability of the emission we performed an analysis searching for VHE gamma-ray signal separating the data set into individual nights. The distribution of the significances of the measured excess is shown in the left panel of Fig. 2. No VHE gamma-ray flare has been observed during the monitoring. Also no significant VHE gamma-ray emission is seen in the total data set of MAGIC monitoring data (see the right panel of Fig. 2).

In Fig. 3 we summarize the measurements obtained during the MWL monitoring campaign. A few interesting enhanced states were observed during this time interval. Increased level of GeV flux is visible around MJD ~ 57650 (dubbed as F1 in the figure). During this period strong optical variability was seen as well, with flares increasing the R-band flux by an order of magnitude. Weak hints of enhanced activity in X-ray and B-band were observed on MJD 58863.7 (dubbed as F2). The MAGIC observations performed during F1 and F2 periods do not show any significant emission.

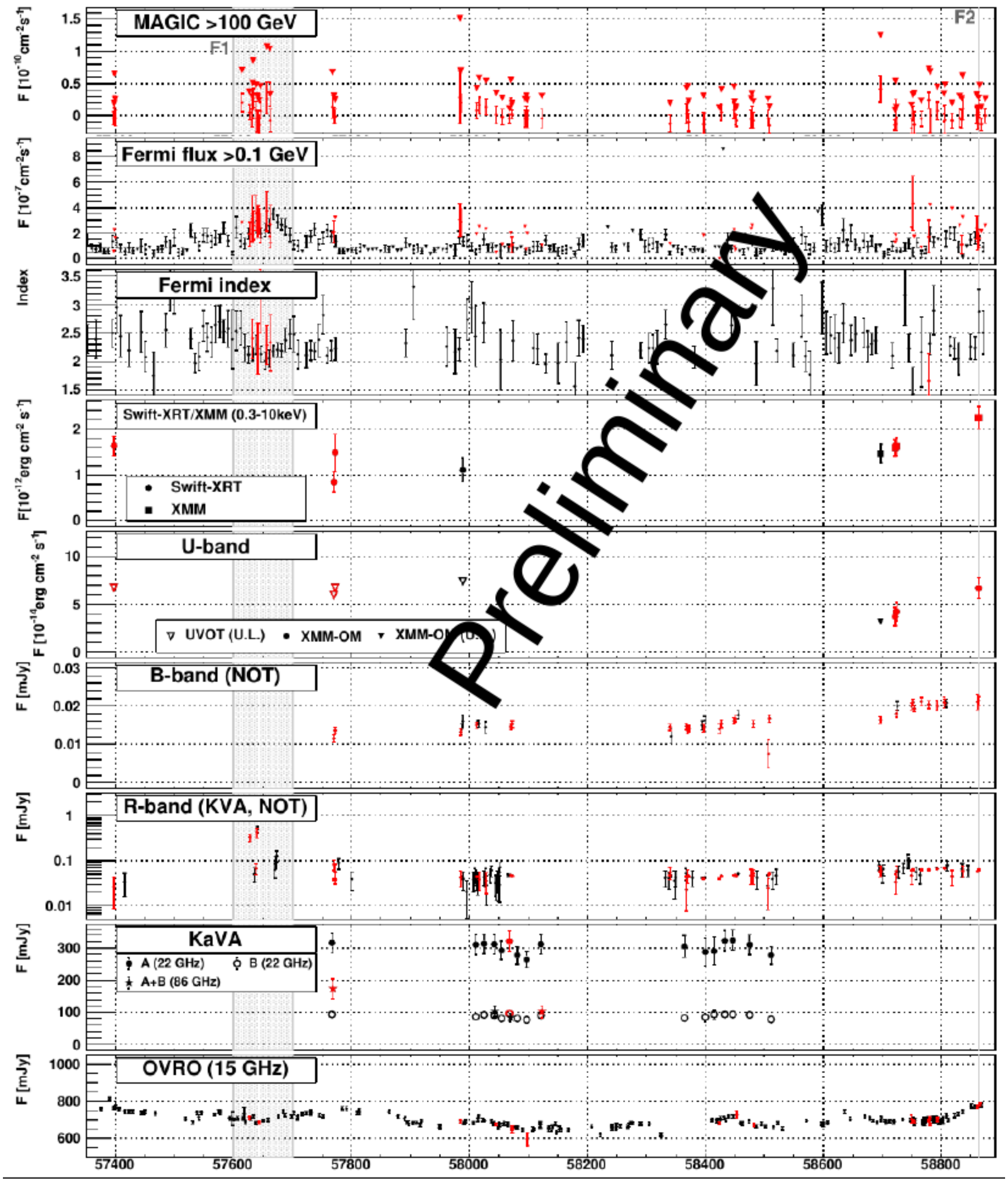

Figure 3: MWL light curve of QSO B0218+357 during 2016-2020 monitoring. From top to bottom: MAGIC flux above 100 GeV, *Fermi*-LAT flux above 0.1 GeV, *Fermi*-LAT spectral index, *Swift*-XRT and *XMM*-Newton X-ray flux in 0.3 – 10 keV range, *Swift*-UVOT and *XMM*-OM U-band, NOT observations in B-band, R-band observations with KVA and NOT. KaVA VLBI observations at 22 GHz (filled symbols show A image, empty ones B image) and 86 GHz (sum of A and B images shown with stars). OVRO monitoring results at 15 GHz. Flux upper limits are shown with downward triangles. The points contemporaneous (within 24 hr slot) with MAGIC observations are marked in red. The gray filled regions mark the enhanced emission periods F1 and F2.

4. Conclusions

We have reported preliminary results from a broadband (radio, optical-UV, X-ray, gamma-ray) monitoring of the only gravitationally-lensed source known as VHE gamma-ray emitter, the FSRQ QSO B0218+357 in 2016-2020. The observation strategy was optimized to facilitate the detection of a VHE gamma-ray flare in both source images. The deep exposure of 72 hrs of data did not reveal low-state VHE gamma-ray emission. A few enhanced emission periods (or hints of enhanced emission) have been seen during the monitoring, however simultaneous MAGIC data did not show transient VHE gamma-ray emission.

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