PROCEEDINGS OF SCIENCE
ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International
Cosmic Ray Conference
12–23 July 2021

Multi-epoch monitoring of TXS 0506+056 with MAGIC and MWL partners

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The measurement of an astrophysical flux of high-energy neutrinos by IceCube is an important step towards finding the long-sought sources of cosmic rays. Nevertheless, the long exposure neutrino sky map shows no significant indication of point sources so far. The real-time follow-up of neutrino events turned out to be the most successful approach in neutrino point-source searches. It brought, among others, the most compelling evidence for a neutrino point source: the flaring gamma-ray blazar TXS 0506+056 in coincidence with a single high-energy neutrino from IceCube (IceCube-170922A). The fast multiwavelength(MWL) follow-up of this alert was key for establishing this coincidence and constraining the subsequent theoretical modeling for this event. In the long run, accurate and contemporaneous MWL spectral measurements are essential ingredients in investigating the physical processes leading to particle acceleration and emission of radiation. A deeper understanding of those processes allows us to put constraints on the potential neutrino emission. Here we present the light curves and simultaneous spectral energy distributions from November 2017 till February 2021 of MAGIC and MWL monitoring of TXS 0506+056. The more than two-year-long rise and high state of the radio light curve of TXS 0506+056, which started near the time of the IceCube neutrino detection, seems to have ended, as indicated by a steep decrease in the first half of 2021. We also present the theoretical interpretation of our observations.

37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany

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[*] Presenter

PoS(ICRC2021)875

1. Introduction

In the context of multimessenger astrophysics, Active Galactive Nuclei (AGN), especially the Blazar class, dominate the very high energy (VHE; > 100 GeV) sky and are considered promising neutrino emitters. AGNs are highly luminous sources, powered by a supermassive black hole and $\sim$10% of them display relativistic jets being natural accelerators of particles. Blazars represent the subclass of AGN with one of the jets pointing very close to the observer's line of sight ($< 10°$), which results in a relativistic boosting of the emission. The radiative processes leading to the emission and the precise composition of the jets are still unknown. Possible explanations rely on leptonic emission schemes or hadronic ones [1–3]. In this second scenario, the VHE photon emission and the neutrino production can be explained as secondary products coming from interactions between accelerated protons and the surrounding photon or matter fields. Although gamma rays can be associated with leptonic processes as well, neutrinos can originate from hadronic interactions only, so their observation would provide us with a unique signature for the presence of highly-relativistic hadrons in the jets.

Several extensive searches for neutrino emission from AGN were performed by the 1km^3 neutrino telescope IceCube, located at the South Pole [4], but up to now no strong correlation between the catalogued AGNs and the observed astrophysical neutrinos has been found. Moreover, blazar contributions to the all-sky astrophysical neutrino flux has been computed and it is constrained at the level of 27% [5]. However, the all-sky astrophysical neutrino flux shows an isotropic distribution, favouring an extragalactic origin. Therefore, AGN still remain as promising neutrino sources.

TXS 0506+056, a bright gamma-ray emitting blazar, is of special interest for the hadronic accelerators case. On September 22, 2017 [6], a 290 TeV neutrino (IceCube-170922A) had been detected in spatial and temporal coincidence with an enhanced γ-ray emission state of this source. This joint observation is currently the only one with a chance coincidence probability disfavoured at the 3σ level. It is so far our most compelling evidence of hadronic emission in blazars. In order to understand the radiative processes at work and the emission mechanism, a multi-wavelength (MWL) monitoring of this source in the long term is essential. In this contribution, we present the data collected by MAGIC and MWL partners from November 2017 till February 2021, including longer periods of low state emission, as well as a VHE γ-ray flaring episode in December 2018.

2. MAGIC monitoring 2017-2021

The source TXS 0506+056 was observed by the the MAGIC telescopes in the period between November 2017 and February 2021 within a dedicated monitoring multiwavelength campaign aimed at collecting long-term data from the source. The total observation time of TXS 0506+056 was of about 128 h, of which about 114 h gave good-quality data, with a zenith angle range between 22° and 50°. These data were analyzed using the MAGIC Analysis Reconstruction Software (MARS) in order to obtain high level products [7, 8].

Figure 1 shows the MAGIC and *Fermi*/LAT lightcurves in the period between November 2017 and February 2020. The former was computed for energies greater than 90 GeV and assuming a spectral index of the source equal to 3.8. The latter was computed for the energy range between

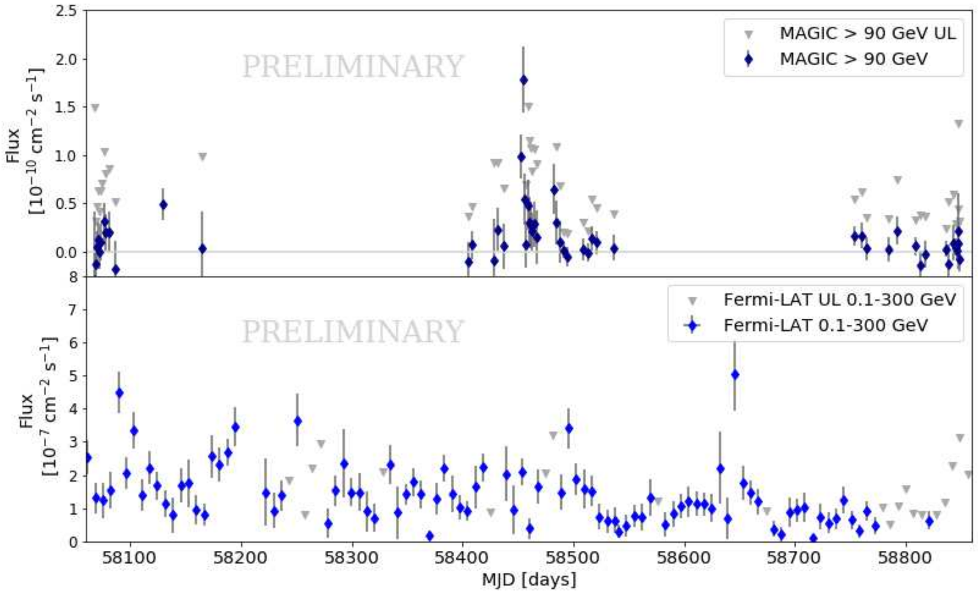

Figure 1: MAGIC and *Fermi*/LAT light curves

100 MeV and 300 GeV in weekly bins. Both results show the source to be in a low state during most of the monitored period (about 110 h), with enhanced emission on December 1^{st} and 3^{rd} 2018 (MJD 58453 and 58455) in the MAGIC energy band and several short flares in the *Fermi*/LAT energy band between 2017 and 2019, showing a different behaviour with respect to the long-term brightening observed in 2017. The obtained VHE fluxes during the flares are F(>90 GeV) = $(9.8 \pm 2.2) \times 10^{-11}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and $(1.8 \pm 3.4) \times 10^{-10}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for December 1^{st} and 3^{rd} respectively, comparable to the flare detected by MAGIC in October 2017, which occurred shortly after the neutrino alert IceCube-170922A [9]. The analysis on observations up to February 2021 is ongoing.

3. Multiwavelength observations

The preliminary multi-band fluxes shown in Fig. 2 were collected from public archives of each instrument. Large parts of these observations were coordinated with MAGIC in order to ensure simultaneous exposure. Dedicated ToO observations were performed with with the Neil Gehrles *Swift* Observatory [10], as well as *NuSTAR* [11]. The MAGIC observations were usually accompanied by the KVA [12] optical telescope, additional measurements were performed with REM after the flare in December 2018. TXS 0506+056 is also systematically monitored by the ASAS-SN project [13]. Clear variability is observed in all wavelengths (Fig. 2)

In the radio band, we have intensified observations of TXS 0506+056 since the IceCube neutrino detection in late 2017. TXS 0506+056 has been observed as part of the Owens Valley Radio Observatory 40-m high-cadence blazar monitoring program at 15 GHz since 2008 [14]. As part of the TANAMI AGN monitoring program, ATCA has been observing TXS 0506+056 at multiple radio frequencies between 5 GHz and 40 GHz since 2009 [15]. In addition, since August 2020, we have been using the Effelsberg 100-m telescope to monitor TXS 0506+056 at four frequencies between 19 GHz and 25 GHz and four frequencies between 36 GHz and 44 GHz as part of the TELAMON program [16].

The Australia Telescope Compact Array (ATCA) is a connected-element radio interferometer of six 22 m diameter dishes, with baseline lengths up to a maximum of 6 km. Observations of TXS 0506+056 were made in "snap-shot" mode with scan lengths of several minutes. Observations in the 7 mm band were preceded by pointing scans on a bright nearby source to refine the global pointing model. All observation bands used a 2 GHz bandwidth. Flux densities are scaled using observations of PKS B1934−638, the ATCA's primary flux density calibrator.

The bottom panel of Fig. 1 shows the long-term radio light curve of TXS 0506+056 between MJD 58100 and 59300 collected by the OVRO, ATCA and TELAMON programs. Around the time of the neutrino detection, the source started a more than 2 yr-long increase in radio flux density from about 600 mJy to more than 2000 mJy. The high-frequency spectral index between 2 cm and 4 cm remains flat throughout this rising phase while the low-frequency brightness at 16 cm (ATCA) is rising more slowly and never reached the same absolute maximum. The rising phase transitioned into a plateau phase in late 2019 in which the source remained through the end of 2020. In 2021, the source shows a steep drop in radio flux density data, which seems to indicate the end of the high radio state that started near the epoch of the IceCube-170922A neutrino detection.

The two distinct activity levels at VHE gamma rays motivated us to produce two broadband SEDs, for the low state and the flaring state, and we modeled this emission using a lepto-hadronic scenario. The largest contemporaneous MWL data sample was collected for the VHE γ-ray low emission state. Its spectral energy distribution shows a clear similarity in shape and flux level at the low energy peak to the one previously observed [9]. The flux level of the high energy peak was measured to be lower than before. For the flaring episode in December 2018, the SED modeling results are compatible with no detection of neutrinos at the time of the VHE γ-ray flare (see Astronomer's Telegrams by ANTARES [17] and IceCube [18]). The MAGIC and MWL data set from the November 2017 to February 2019 campaign, including the SED modeling, will be discussed in details in a separate publication.

4. Summary and Outlook

TXS 0506+056 is a key object to help the astrophysics community to establish connections between high-energy neutrinos and astrophysical sources. Accurate and contemporaneous MWL spectral measurements are essential ingredients to achieve this goal. Here, we presented the results from the MAGIC and MWL monitoring of this source, spanning the time period from November 2017 till February 2021.

In comparison to the previously published results, TXS 0506+056 displayed a very low VHE γ-ray emission state during most of the observed nights, with the exception of the flaring activity observed on December 1^{st} and 3^{rd} 2018. The MAGIC Collaboration will continue to monitor the source in the next observation season from September 2021 to February 2022.

The MWL light curve shows clear signs of variability, especially in the high energy range (X-ray and HE γ-ray). A long-term rising trend in the radio band was observed until the end of

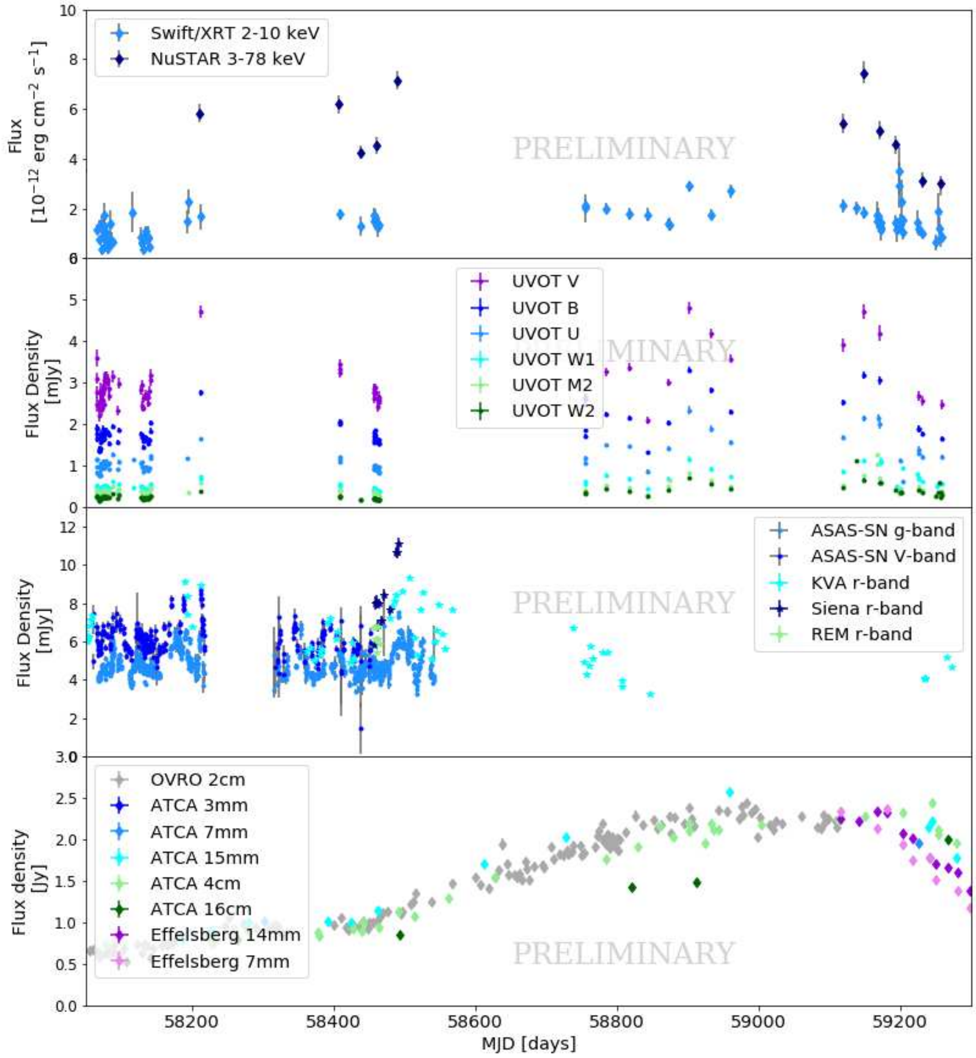

Figure 2: Multi-wavelength light-curve of during the 2017-2019 campaign. From top to bottom: X-rays (*Swift*/XRT and *NuSTAR*); UVOT; optical (ASAS-SN, KVA, REM, Siena); radio: ATCA, Effelsberg and OVRO.

2020, transitioning in a steep decay at the beginning of 2021. Investigation of the MWL correlations is on-going and will be a subject of a separate publication.

5. Acknowledgments

The members of the MAGIC Collaboration gratefully acknowledge financial support from the agencies and organizations listed here: `https://magic.mpp.mpg.de/acknowledgments_ICRC2021`

This research is partly based on observations with the 100-m telescope of the MPIfR (Max-Planck-Institut für Radioastronomie) at Effelsberg.

This research has made use of data from the OVRO 40-m monitoring program which was supported in part by NASA grants NNX08AW31G, NNX11A043G and NNX14AQ89G, and NSF grants AST-0808050 and AST-1109911, and private funding from Caltech and the MPIfR.

The Australia Telescope Compact Array is part of the Australia Telescope National Facility which is funded by the Australian Government for operation as a National Facility managed by CSIRO. We acknowledge the Gomeroi people as the traditional owners of the Observatory site.

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