

The Aftermath of an Exceptional TeV Flare in the AGN Jet of IC 310

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Abstract: The nearby active galaxy IC 310 ($z = 0.019$), located in the Perseus cluster of galaxies is a bright and variable multi-wavelength emitter from the radio regime up to very high gamma-ray energies above 100 GeV. Very recently, a blazar-like compact radio jet has been found by parsec-scale VLBI imaging. Along with the unusually flat gamma-ray spectrum and variable high-energy emission, this suggests that IC 310 is the closest known blazar and therefore a key object for AGN research.

As part of an intense observing program at TeV energies with the MAGIC telescopes, 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. We have organized a multi-wavelength follow-up program, including the VLBA, Effelsberg 100 m, KVA, *Swift*, *INTEGRAL*, *Fermi*/LAT, and the MAGIC telescopes.

We present preliminary results from the multi-wavelength follow-up program with the focus on the response of the jet to this exceptional gamma-ray flare.

Keywords: BL Lacertae objects - IC 310 - multi-wavelength campaigns - VHE observations

1 Introduction

Active galactic nuclei (AGN) harbor the most extreme objects in the Universe. They exhibit supermassive black holes with up to 10^{10} solar masses surrounded by an accretion disk and a dust torus. Perpendicular to the plane of the disk and the torus, collimated relativistic plasma outflows are ejected away from the AGN. Particular AGN are the so-called blazars for which the angle between those jets and the line-of-sight is believed to be small. Those objects are dominated by non-thermal emission observed at all wavelengths of the electromagnetic spectrum. They are characterized by rapid variations of their flux seen in all energy bands from radio to gamma-ray. In contrast, radio galaxies are AGN where the angle to the line-of-sight is large.

Most of the AGN detected up to the very high energy (VHE) regime (> 100 GeV) belong to the class of blazars. So far only three objects, M 87, Centaurus A, and NGC 1275 which are radio galaxies were discovered to be VHE emitters as well.

The nearby ($z = 0.019$) lenticular (S0) galaxy IC 310 exhibits an AGN, which has been detected at gamma-ray energies above 30 GeV with *Fermi*/LAT [1] as well as above 260 GeV with the MAGIC telescopes [2, 3]. The measured

spectrum in the gamma-ray band is very hard.

In the past, the object was thought to be a head-tail radio galaxy [4]. Those are typically found in clusters of galaxies and are characterized by their extended jets which are pointing in the direction determined by the galaxy's motion through the intra-cluster medium (ICM). In contrast to this classification, a milliarcsecond-scale one-sided blazar-like jet oriented along the same position angle as the kiloparsec scale radio structure has been found for IC 310 at 8.4 GHz [5] and confirmed by MOJAVE observations at 15 GHz (see Fig. 1). Assuming that the one-sidedness is due to Doppler boosting, the angle between the jet axis of the AGN and the line-of-sight has been estimated to be $< 38^\circ$ [5]. The stability of the jet orientation from parsec to kiloparsec scales in IC 310 argues against its classification as a head-tail radio galaxy, i.e., there is no indication of an interaction with the intracluster medium that would determine the direction of the tail.

In [6, 5] the authors suggested already that IC 310 belongs to a transitional population between BL Lac and FR I (i.e. low power) radio galaxy based on the optical, radio and X-ray observational results of the source. The weak optical emission lines of IC 310 are typically found for FR I radio galaxies but its radio to X-ray non-thermal contin-

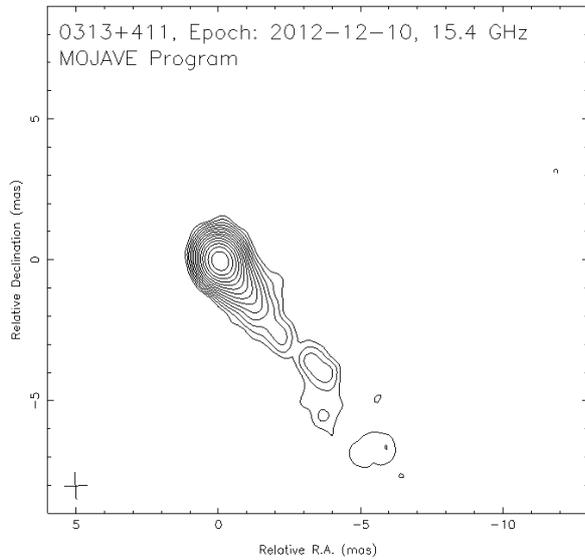


Figure 1: Parsec-scale jet of IC 310 as measured with the VLBA at 15 GHz on December 12, 2012 as part of the MOJAVE project. The lowest contour and the brightness peak are $0.17 \text{ mJy beam}^{-1}$ and $73.0 \text{ mJy beam}^{-1}$. The beam has a size of $0.98 \times 0.82 \text{ mas}$ at 3.5° . The image has been taken from <http://www.physics.purdue.edu>.

uum is similar to low-luminosity BL Lac objects [7]. Observations by *XMM-Newton* [8] showed the X-ray emission to be dominated by nuclear emission with a featureless power-law X-ray spectrum that is typical for a BL Lac-type object, as well. *Chandra* observations show a faint X-ray halo extending in the direction of the radio tail [9].

The observational data, showing daily TeV flux variability and strong variability in the X-ray spectra and flux, suggest that IC 310 is either the closest known blazar as already suggested by [5, 3] or one of four VHE loud radio galaxies.

2 Observation Campaign and Results

The first successful multi-wavelength campaign on IC 310 was started in autumn 2012 after high resolution Very Long Baseline Interferometry (VLBI) was conducted with the European VLBI Network.

For this campaign, VHE observations of IC 310 were carried out between November 2012 and January 2013 with the MAGIC telescopes which are two Imaging Atmospheric Cherenkov Telescopes located on the island of La Palma at an altitude of 2200 m. Both telescopes consist of a mirror dish of 17 m diameter associated with a fast imaging camera of 3.5° field-of-view. In summer 2011 to autumn 2012 the MAGIC telescopes underwent a major upgrade in order to assure a stable performance and operation of the telescopes for the upcoming years [11]. The upgrade included a replacement of the readout system of both telescopes with a digitizing system based on the DRS-4 chip and a new MAGIC-I camera, a clone of the MAGIC-II camera, equipped with 1039 channels of 0.1° pixels, increasing the trigger region.

Optical observations were performed with the Kungliga

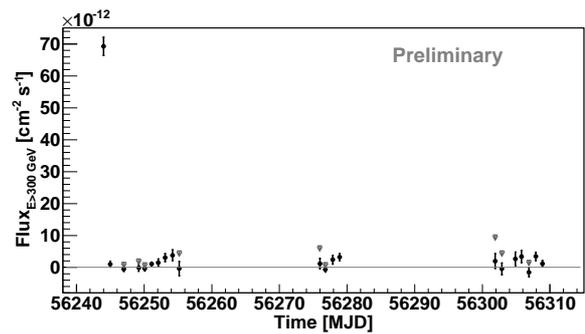


Figure 2: Light curve of IC 310 measured with MAGIC above 300 GeV between November 2012 to January 2013. The upper limits were calculated applying the method by [10], using a confidence level of 95% and assuming 30% systematic uncertainty.

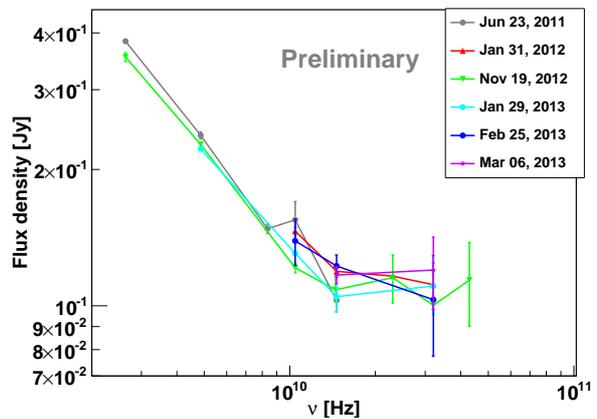


Figure 4: Flux-density measurements with the Effelsberg 100-m telescope as a function of frequency at different epochs. As of March 6, 2013, no enhancement of the flux density at the highest frequencies after the TeV flare has been observed.

Vetenskapsakademien (KVA) 35 cm telescope on La Palma that operates in close collaboration with the MAGIC telescopes as well as with optical telescopes at the Observatoire de Haute Provence (France). Additionally, further observations in the radio band were conducted by the Effelsberg 100 m telescope and data from the OVRO blazar monitoring program at 15 GHz have been used for this campaign [12]. VLBI monitoring observations at 15 GHz were commenced as part of the MOJAVE project [13], see also Fig. 1. The UV and the X-ray coverage was provided by Target of Opportunity observations organized with *Swift*. The hard X-ray and soft gamma-ray regime has been covered by *Swift*/BAT, *INTEGRAL* and *Fermi*/LAT.

The preliminary light curve measured by MAGIC above 300 GeV is shown in Fig. 2, and comprised with multi-wavelength data in Fig. 3. The analysis of the *INTEGRAL* data is in progress.

During this campaign MAGIC observations carried out on MJD 56243.9-56244.1 detected the highest flare ever detected from IC 310 in the VHE range [14]. The analysis resulted in a detection with the significance of ~ 25

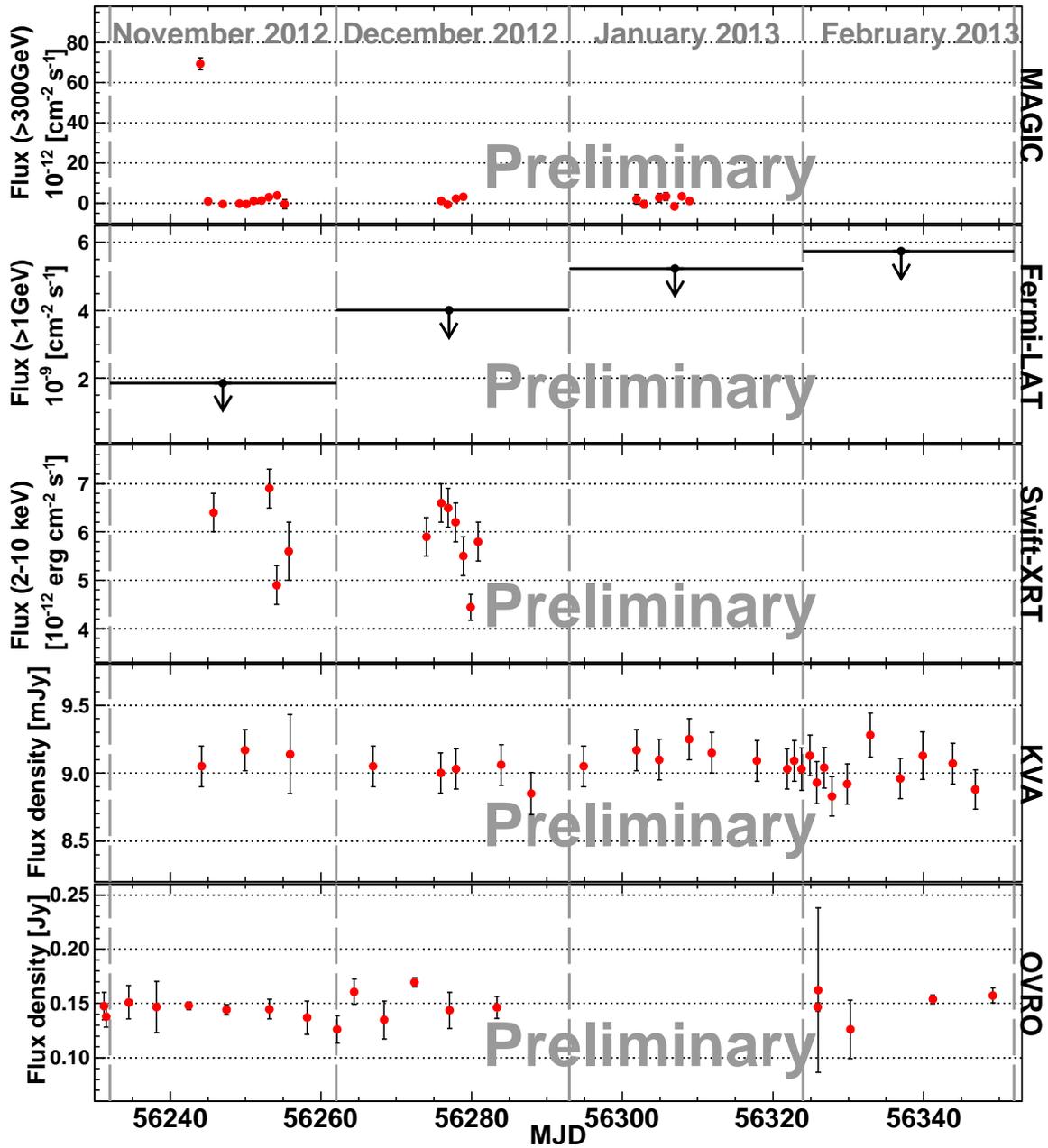


Figure 3: Multi-wavelength light curve of IC 310. *Top to bottom panel:* MAGIC above 300 GeV, *Fermi-LAT* above 1 GeV, *Swift-XRT*, KVA R-band data and, OVRO at 15 GHz from November 2012 to February 2013. The optical data from KVA presented here are not host-galaxy corrected.

standard deviations (σ). The mean flux above 300 GeV is 56% of the Crab Nebula flux (C.U.). During previous observations in 2009/2010 this mean flux was measured to be $(2.5 \pm 0.4)\%$ C.U. [2] and $(12.8 \pm 0.1)\%$ C.U. for the high state flux reported in [3].

Quasi-simultaneous observations of IC 310 after the VHE flare were performed on MJD 56245.67 with *Swift* [15]. The spectrum of IC 310 was observed to be similar to an earlier *Swift*-observation in January 2012, but a factor of 1.5 brighter. Based on the *Swift* quick-look-data, the count rate was 0.24 counts/s (0.5–10 keV). The spectrum can be well described by an absorbed power law with a photon index of 1.94 ± 0.16 and $N_H = (1.3 \pm 0.4) \times 10^{21} \text{ cm}^{-2}$, corresponding to a 2–10 keV flux of $(6.4 \pm 0.8) \times 10^{-12} \text{ cgs}$.

The measured N_H value is consistent with the Galactic 21 cm N_H as obtained from the Leiden-Argentine-Bonn survey [16]. In January 2012, the photon index was 2.14 ± 0.12 . Compared to the February 26, 2003 *XMM-Newton* observations of IC 310 [8] the source flux was enhanced by a factor of 4.6 and the source spectrum was significantly harder (*XMM-Value*: 2.5). Further *Swift* observations during the campaign show a hint for variability of the flux of the order of $\sim 3\sigma$ in the 2–10 keV band.

After the VHE flare the UV flux observed by *Swift*-UVOT is virtually unchanged compared to previous observations and appears to be dominated by the host galaxy. The same behavior is seen for the optical data from KVA.

The radio data from OVRO at 15 GHz show no signifi-

cant variability. The radio spectra obtained from Effelsberg show no large variations (see Fig. 4).

3 Discussion and Conclusion

We present preliminary results from the first multi-wavelength campaign of the TeV loud object IC 310. We interpret the variable emission from X-ray to VHE to originate from the central blazar-like engine rather than being produced by interactions with the ICM. During those observations, an exceptional TeV flare has been detected with MAGIC.

Several authors have reported a coincidence between the ejection of new radio components in VLBI maps and high gamma-ray flux periods from different blazars [18, 19, 20]. The typical timescale between a gamma-ray flare and the ejection are between less than one month and several months. The VHE flare observed from IC 310 in November 2012 gives the opportunity to study in detail the response of an individual radio jet to an unprecedented VHE flare. As IC 310 is included in the MOJAVE program the pc-scale jet has been monitored. Additionally, the radio spectrum of IC 310 has been observed with the Effelsberg telescope to find evidence for such an ejection. Especially at higher frequencies, e.g., above 10 GHz where the radio emission is dominated by a flat blazar-like spectrum (see Fig. 4), any enhancement of the flux density could indicate a new radio component appearing in the jet. Below 10 GHz the spectrum is steep, indicating extended, optically thin emission. As of February 2013, the radio monitoring did not show any significant response of the radio jet.

A more detailed analysis of the extensive amount of multi-wavelength data is currently ongoing.

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