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

DORIT EISENACHER1, PIERRE COLIN2, SAVERIO LOMBARDI3, JULIAN SITARER4, FABIO ZANDANEL5,12, FRANCISCO PRADA3, ELINA LINFORS5, DAVID PANEQUE2, DOMINIK ELSÄSSER1, KARL MANNHEIM1, FOR THE MAGIC COLLABORATION, CORNELIA MÜLLER1,7, FOR THE Fermi/LAT COLLABORATION, THOMAS DAUSER7, FELICIA KRAUSS2, SVEN WILBERT3, MATTHIAS KADLER1, JÖRN WILMS2, UWE BACH8, EDUARDO ROJS9,10,8, TALVIKKI HOVATTA11, FOR THE OVO TEAM, TUOMAS SAVOLAINEN11, FOR THE MOJAVE TEAM

1 Universität Würzburg, D-97074 Würzburg, Germany
2 Max-Planck-Institut für Physik, D-München, Germany
3 INAF National Institute for Astrophysics, I-00136 Rome, Italy
4 IFAE, Edifici Cn., Campus UAB, E-08193 Bellaterra, Spain
5 Inst. de Astrofísica de Andalucía (CSIC), E-18080 Granada, Spain
6 Turku Observatory, University of Turku, FI-21500 Piikkiö, Finland
7 De Remeis-Sternwarte Bamberg, Astronomisches Institut der Universität Erlangen-Nürnberg, ECAP, D-96049 Bamberg, Germany
8 Max-Planck-Institut für Radioastronomie, D-53121 Bonn, Germany
9 Observatori Astronòmic, Universitat de València, E-46980 Paterna, València, Spain
10 Departament d’Astronomia i Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain
11 Cahill Center for Astronomy & Astrophysics, California Institute of Technology, Pasadena, CA 91125, USA
12 now at: GRAPPA Institute, University of Amsterdam, N-1098XH Amsterdam, Netherlands

Dorit.Eisenacher@astro.uni-wuerzburg.de

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 10^9 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/LAT12 as well as above 260 GeV with the MAGIC telescopes2,3. The measured spectrum in the gamma-ray band is very hard.

In the past, the object was thought to be a head-tail radio galaxy4. 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 GHz5 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°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.

In6,7 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-
An Exceptional TeV Flare in the AGN Jet of IC 310

33ND INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013

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 mJy beam$^{-1}$ and 73.0 mJy beam$^{-1}$. The beam has a size of 0.98 × 0.82 mas at 3.5°. The image has been taken from http://www.physics.purdue.edu.

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.

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 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. 4 and comprised with multi-wavelength data in Fig. 5. 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
An Exceptional TeV Flare in the AGN Jet of IC 310

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 ± 0.4)% C.U. [2] and (12.8 ± 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 $N_H = (1.3 \pm 0.4) \times 10^{21}$ cm$^{-2}$, corresponding to a 2–10 keV flux of $(6.4 \pm 0.8) \times 10^{-12}$ 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-
The Very Long Baseline Array (VLBA) is operated by the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement with the Associated Universities, Inc. The OVRO 40 M Telescope Fermi Blazar Monitoring Programme by Associated Universities, Inc.

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. 3), 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.

Acknowledgment: We would like to thank the Instituto de Astrofísica de Canarias for the excellent working conditions at the Observatorio del Roque de los Muchachos in La Palma. The support of the German BMBF and MPG, the Italian INFN, the Swiss National Fund SNF, and the Spanish MICINN is gratefully acknowledged. This work was also supported by the CPAN CSD2007-00042 and MultiDark CSD2009-00064 projects of the Spanish Consolider-Ingenio 2010 programme, by grant DO02-1071 of the Bulgarian NSF, by grant 127740 of the Academy of Finland, by the DFG Cluster of Excellence “Origin and Structure of the Universe”, by the DFG Collaborative Research Centers SFB823/C4 and SFB876/C3, and by the Polish MNiSzW grant 745/N-HESS-MAGIC/2010/0. The Fermi-LAT Collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy and CNES in France for science analysis during the operations phase is also gratefully acknowledged.

This research has made use of data obtained from the High Energy Astrophysics Science Archive Research Center (HEASARC), provided by NASA’s Goddard Space Flight Center. This work is 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 MOJAVE database that is maintained by the MOJAVE team (Lister et al., 2009, AJ, 137, 3718). The Very Long Baseline Array (VLBA) is operated by the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement with Associated Universities, Inc. The OVRO 40 M Telescope Fermi Blazar Monitoring Program is supported by NASA under awards NNX08AW31G and NNX11AO43G, and by the NSF under awards AST-0808050 and AST-1109911. This work made use of the Swinburne University of Technology software correlator (Deller et al., 2011, PASP, 123, 275), developed as part of the Australian Major National Research Facilities Programme and operated under licence. E. R. was partially supported by the Spanish MINECO projects AYA2009-1306-C02-02 and AYA2012-38491-C02-01 and by the Generalitat Valenciana project PROMETEO/2009/104, as well as by the COST MP0905 action ‘Black Holes in a Violent Universe’.

References

[1] Neronov et al., A&A, 2010, 519, L6
[2] Aleksie et al., ApJ, 2010, 723, L207
[3] Aleksie et al. 2013, submitted, arXiv:1305.5147
[4] Sijbring & de Bruyn, A&A, 1998, 331, 901
[5] Kadler et al., A&A, 2012, 538, L1
[6] Rector et al., ApJ, 1999, 516, 145
[7] Owen et al., AJ, 1996, 111, 53
[8] Sato et al., PASJ, 2005, 57, 743
[9] Dunn et al., MNRAS, 2010, 404, 180
[10] Rolke et al., Nucl. Instrum. Meth., 2005, 551, 493
[11] Mazin et al., Proc. of the 33rd ICRC, Rio de Janeiro, Id. 1071
[12] Richards et al., ApJS, 2011, 194, 29
[13] Lister et al., AJ, 2009, 137, 3718
[14] Cortina, ATel #4583, 2012
[15] Krauß et al., ATel #4581, 2012
[16] Kalberla et al., Astron. Astrophys., 2005, 440, 775
[17] Nolan et al., ApJS, 2012, 199, 31
[18] Jorstad et al., ApJ, 2001, 556, 738
[19] Marscher et al., Nature, 2008, 452, 966
[20] Kovalyev et al., ApJ, 2009, 696, L17