First multi-wavelength campaign on the gamma-ray-loud active galaxy IC 310

(The MAGIC Collaboration),
(Affiliations can be found after the references)

Received 23 December 2016 / Accepted 21 March 2017

ABSTRACT

Context. The extragalactic very-high-energy gamma-ray sky is rich in blazars. These are jetted active galactic nuclei that are viewed at a small angle to the line-of-sight. Only a handful of objects viewed at a larger angle are so far known to emit above 100 GeV. Multi-wavelength studies of such objects up to the highest energies provide new insights into the particle and radiation processes of active galactic nuclei.

Aims. We aim to report the results from the first multi-wavelength campaign observing the TeV detected nucleus of the active galaxy IC 310, whose jet is observed at a moderate viewing angle of 10°–20°.

Methods. The multi-instrument campaign was conducted between 2012 November and 2013 January, and involved observations with MAGIC, Fermi, INTEGRAL, Swift, OVRO, MOJAVE and EVN. These observations were complemented with archival data from the AllWISE and 2MASS catalogs. A one-zone synchrotron self-Compton model was applied to describe the broadband spectral energy distribution.

Results. IC 310 showed an extraordinary TeV flare at the beginning of the campaign, followed by a low, but still detectable TeV flux. Compared to previous measurements in this energy range, the spectral shape was found to be steeper during the low emission state. Simultaneous observations in the soft X-ray band showed an enhanced energy flux state and a harder-when-brighter spectral shape behavior. No strong correlated flux variability was found in other frequency regimes. The broadband spectral energy distribution obtained from these observations supports the hypothesis of a double-hump structure.

Conclusions. The harder-when-brighter trend in the X-ray and VHE emission, observed for the first time during this campaign, is consistent with the behavior expected from a synchrotron self-Compton scenario. The contemporaneous broadband spectral energy distribution is well described with a one-zone synchrotron self-Compton model using parameters that are comparable to those found for other gamma-ray-emitting misaligned blazars.

Key words. galaxies: active – galaxies: individual: IC 310 – gamma rays: galaxies

* Corresponding author: D. Eisenacher Glawion, e-mail: dlglawion@1sw.uni-heidelberg.de
1. Introduction

An active galactic nucleus (AGN) emits radiation over a broad band of the electromagnetic spectrum. Radio-loud AGNs form a subclass in which plasma jets are found to be perpendicularly extending away from the central region consisting of an accretion disk and a supermassive black hole (BH). In the very-high-energy (VHE) gamma-ray range (50 GeV ≤ E ≤ 50 TeV), sixty-six of these objects have been detected so far\(^1\). Most of these objects fall into the subcategory of blazars. They are characterized by strong variability in all energy bands and on all timescales. According to the unified scheme for radio-loud AGNs (Urry & Padovani 1995), blazars are believed to be AGNs viewed at a small angle between the jet-axis and the line-of-sight. Hence, a strong Doppler beaming effect is expected to play a major role in the explanation of the observational properties. Only a few of the detected VHE objects belong to the class of radio galaxies or misaligned blazars: Centaurus A (Aharonian et al. 2009), M 87 (Aharonian et al. 2003; 2006, Acciari et al. 2008, 2009, Albert et al. 2008), NGC 1275 (Aleksić et al. 2012, 2014b), IC 310 (Aleksić et al. 2010, 2014a,c), and PKS 0625−354 (Dyrdal et al. 2015). Radio galaxies and misaligned blazars are viewed at a larger angle to the jet-axis; therefore, the Doppler boosting effect is smaller compared to blazars.

Due to the small Doppler-boosting effect and often measurable viewing angle, various acceleration and radiation models for the high-energy emission of radio-loud AGNs can be well studied for radio galaxies. This investigation requires multiwavelength (MWL) data of such objects, preferably simultaneous and with good observational coverage due to their variable behavior. For all these objects, except for IC 310 and PKS 0625−354, extensive MWL campaigns up to the VHE range have been conducted and reported previously (Abdo et al. 2009b, 2010a; Acciari et al. 2009; Aleksić et al. 2014b).

IC 310 is located on the outskirts of the Perseus galaxy cluster with a redshift of \( z = 0.0189 \) (Bernardi et al. 2002). Originally, this object was classified as a head-tail radio galaxy (Ryle & Windram 1968; Miley 1980; Sijbring & de Bruyn 1998). However, observations in different frequency bands indicated that it is, in fact, a transitional object (Aleksić et al. 2014a) with a viewing angle of \( 10° < \theta < 20° \) (Aleksić et al. 2014c), showing properties similar to a radio galaxy, for example, a one-sided parsec-scale jet (Kadler et al. 2012). While weak optical emission lines observed from IC 310 are typically found in radio galaxies (Owen et al. 1996), Rector et al. (1999) identified IC 310 as possible low-luminosity BL Lac object. The X-ray emission is mostly point-like as observed with ROSAT and XMM-Newton (Schwarz et al. 1992; Rhee et al. 1994; Sato et al. 2005) whereas a hint of X-ray halo emission in the direction of the observed kpc radio jet has been reported by Dunn et al. (2010). In the soft X-ray band, the flux and spectral vary in a manner typical for blazars (Aleksić et al. 2014a). In the gamma-ray band, IC 310 was first detected with the Fermi-Large Area Telescope (LAT) at energies above 30 GeV by Neronov et al. (2010) and with the MAGIC telescopes above 260 GeV (Aleksić et al. 2010).

In this paper we present the results from the first MWL campaign, conducted between 2012 and 2013. The publication is structured as follows: the observations of all participating instruments and the data analysis are described in Sect. 2 from higher to lower frequencies. In Sect. 3, the observational results are presented. The assembled MWL light curve and spectral energy distribution (SED) will be discussed in Sect. 4, followed by the summary and conclusions in Sect. 5.

2. Multi-wavelength observations and data analysis

The MWL campaign for IC 310 in 2012 and 2013 included observations from radio up to the highest energies with space- and ground-based telescopes. Even while the campaign did not aim to observe the source in a high state, serendipitously a bright TeV flare with minute timescale variability was detected in 2012 November by MAGIC (Aleksić et al. 2014c). Participating instruments in the radio band were OVRO (single-dish) as well as the very-long-baseline interferometry (VLBI) arrays: European VLBI Network (EVN) and the VLBA through the “Monitoring Of Jets in Active galactic nuclei with VLBA Experiment” (MOJAVE) project at cm wavelengths. In the optical and ultraviolet band, measurements were provided by KVA and Swift-UVOT. The X-ray regime was covered by Swift-XRT and -BAT, and INTEGRAL. Fermi-LAT and MAGIC permitted the high-energy (HE, 20 MeV ≤ E ≤ 100 GeV) and VHE gamma-ray measurements. In the following section, the observations of IC 310 and the data analysis is described.

2.1. Very high energy: the MAGIC telescopes

MAGIC is a system of two Imaging Air Cherenkov telescopes, both 17 m in diameter, located on the Canary Island of La Palma, Spain. It covers the electromagnetic spectrum in the VHE range from 50 GeV to 50 TeV and achieves an angular resolution of ~0.1° (Aleksić et al. 2016b).

The observations during the MWL campaign were conducted after the upgrade of the two telescopes in 2011–2012 was completed (Aleksić et al. 2016a). On the first night of observation, 2012 November 12–13 (MJD 56 243.95–56 244.11), during 3.7 h of observation, MAGIC detected a bright flare as reported in Aleksić et al. (2014c). Further observations up to 2013 January 17 (MJD 56.309.1) were carried out as part of the MWL campaign during day and moon time. Data affected by non-optimal weather conditions were discarded. Only observations during dark night and with moderate moon light were selected, and the standard analysis (Aleksić et al. 2016b) can be applied. After the selection, the data set consists of ~39 h including the data of the flaring night. The data cover the zenith distance range of 11° < Zd < 56°.

Data analysis was performed analogously to Aleksić et al. (2014c, 2016b). Image cleaning was performed using the dynamical sum-cleaning algorithm presented in Sitarek et al. (2013). The significance of the signal was calculated from Eq. (17) of Li & Ma (1983) using four background regions that do not overlap with the emission from NGC 1275, which is a VHE object 0.6° away from IC 310. Flux and differential upper limits are calculated according to Rolke et al. (2005) using a 95% confidence level. Following Aleksić et al. (2016b), we considered the following systematic errors for the spectra: 11% for the flux normalization, 15% for the energy scale and 0.15 for the photon index. As reported previously in Aleksić et al. (2014a,c), the absorption due to the extragalactic background light (EBL) is only marginal for IC 310. The intrinsic spectra presented in this paper are calculated using the model of Domínguez et al. (2011).
2.2. High energy: Fermi-LAT

Fermi was launched in 2008 June and since 2008 August 5, it is operated primarily in sky survey mode, scanning the entire sky every three hours (Atwood et al. 2009). The Fermi-LAT is a pair-conversion telescope sensitive to photons between 20 MeV and several hundred GeV (Ackermann et al. 2012).

We calculated spectra using the Fermi Science Tools (v10r0p5)\(^2\) for the time period 2012 November 01 (MJD 56,232) to 2013 January 31 (MJD 56,323). We used the Pass 8 data, the recommended P8R2\_SOURCE\_V6 instrumental response functions, the isotropic diffuse background template iso\_P8R2\_SOURCE\_V6\_v06 and the Galactic emission model gll\_iem\_v06 (Acero et al. 2016)\(^3\), a region of interest (ROI) with a radius of 10° and an energy range of 1–300 GeV. We ran the unbinned likelihood analysis with a 90° zenith angle cut to reduce contamination from the Earth limb. As an input for the likelihood analysis we used the 3FGL model (Acero et al. 2015). For sources within the ROI the photon index and prefactor (and equivalent for other models) were left free. Spectral upper limits are calculated with a limiting test statistic (TS) of 25 (Mattox et al. 1996), and taking into account sources in the spectral model of a radius of 20°. The predicted number of counts is low (approximately ten). Because NCG 1275 appears to be very bright and close to IC 310 with an offset of 0.6°, the results reported here are calculated for energies higher than 1 GeV to mitigate the effects of a larger point-spread function at lower energies\(^4\).

2.3. X-ray: INTEGRAL, Swift-BAT/XRT

The International Gamma-Ray Astrophysics Laboratory (INTEGRAL) satellite has been in operation since late 2002 (Winkler et al. 2003). It is equipped with several instruments in the hard X-ray to soft gamma-ray range; the high resolution spectrometer SPI at 20 keV–8 MeV (Vedrenne et al. 2003), and two high angular resolution gamma-ray imagers, called IBIS, which operate at 15–1000 keV and 0.175–10.0 MeV (Ubertini et al. 2003). It is equipped with several instruments in the hard X-ray to soft gamma-ray range: the high resolution spectrometer SPI at 20 keV–8 MeV (Vedrenne et al. 2003), and two high angular resolution gamma-ray imagers, called IBIS, which operate at 15–1000 keV and 0.175–10.0 MeV (Ubertini et al. 2003).

The IBIS data were extracted using the Offline Science Analysis tool OSA, version 10.1. All data between 2012 August and 2013 February are taken into account, where IC 310 was located within 14° from the pointing center, resulting in 451 science windows. These data were filtered for the energy range between 20 keV and 200 keV. No significant signal was detected from these data and upper limits are derived. SPI data were not used for this publication.

The Swift satellite was launched in late 2004 (Gehrels et al. 2004). Swift provides measurements with telescopes covering the optical and X-ray (soft and hard) ranges. Continuous observations in the hard X-ray range (15–150 keV), mainly for detecting gamma-ray bursts, are provided by the Burst Alert Telescope (BAT). The X-Ray Telescope (XRT) operates in the soft X-ray regime from 0.2 to 10 keV (Burrows et al. 2005).

We extracted a spectrum in the energy band of 20–100 keV from the 104-month Swift-BAT survey maps and fit the spectrum with a simple power law with fixed normalization. A fitting-statistic for Poisson-distributed source count rates and Gaussian-distributed background count rates as recommended in the XSPEC statistics appendix was used\(^5\). The calculations of the flux, photon index, and the corresponding 90% uncertainties were implemented using Monte Carlo simulations of the spectrum.

Furthermore, observations of IC 310 with the Swift-XRT with a total exposure of 45.8 ks were performed in 2012 November and December. The results presented here are compared to earlier observations of 13.2 ks taken in January of the same year. The XRT data were reduced with standard methods, using the most recent software packages (HEASOFT 6.15.1) and calibration databases. Spectra were grouped to a minimum signal-to-noise ratio of five to ensure the validity of \(\chi^2\) statistics. For the broadband SED we applied another re-binning in order to increase the significance of individual points. Spectral fitting was performed with ISIS 1.6.2 (Houck & Denicolà 2000). We fit the 0.5–10 keV energy band with an absorbed power-law model, which yielded a good fit probability. X-ray data were de-absorbed using abundances from Wilms et al. (2000) and cross sections from Verner et al. (1996). As previous Chandra observations (Aleksić et al. 2014a) revealed a \(N_H\) significantly above the Galactic \(N_H\) value of 0.12 \(\times 10^{22}\) cm\(^{-2}\) for IC 310 (Kalberla et al. 2010) we left \(N_H\) free in the fit.

2.4. Ultraviolet and optical: Swift-UVOT, KVA

In addition to the X-ray instruments, Swift is equipped with the UltraViolet/Optical Telescope (UVOT) providing observations in the ultraviolet (UV) and optical ranges simultaneous with the XRT (Gehrels et al. 2004). The telescope is equipped with the following filters: V (547 nm), B (439 nm), U (347 nm), UVW1 (225 nm), UVM2 (225 nm), and UVW2 (193 nm). Swift-UVOT data were extracted following standard methods\(^6\).

The Kungliga Vetenskaps Akademien (KVA) telescopes are located at the Observatorio del Roque de los Muchachos on the island of La Palma, Spain, and are operated by the Tuorla observatory\(^7\). They consist of two optical telescopes with mirror diameters of 60 cm and 35 cm. Filters in the R-band (640 nm), B-band (550 nm), and V-band (440 nm) are available. The photometric observations were conducted with the R-band filter and the 35 cm telescope during the MAGIC observations. The data were analyzed using a standard semi-automatic pipeline. The brightness of the source was measured using differential photometry with a standard aperture radius of 5.0°. The host galaxy emission is expected to be constant. Any AGN variability would affect the light curve. Optical, infrared, and ultraviolet data were de-reddened using the same absorbing columns obtained from the Swift-XRT data (Nowak et al. 2012, and references therein).

2.5. Radio: OVRO, EVN, VLBA/MOJAVE

The 40 m Owens Valley Radio Observatory (OVRO, California, USA) telescope provides radio data for a list of AGNs at 15 GHz nearly twice per week since 2008\(^8\). Details on the observing strategy and the calibration procedures are summarized in Richards et al. (2011). The data presented in this paper cover the light curve. Optical, infrared, and ultraviolet data were de-reddened using the same absorbing columns obtained from the Swift-XRT data (Nowak et al. 2012, and references therein).

\(^2\) Available online at http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/
\(^3\) http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html
\(^4\) The plot of the point-spread function can be found online at https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm
\(^6\) http://swift.gsfc.nasa.gov/analysis/UVOT_swguide_v2_2.pdf
\(^7\) http://users.utu.fi/kani/1m
\(^8\) http://www.astro.caltech.edu/ovroblazars/
the time range from 2012 October 31 (MJD 56 231) to 2012 December 22 (MJD 56 283).

The European VLBI Network is a consortium of several radio-astronomical institutes and telescopes from Europe, Asia, and South Africa\(^9\). Due to the large collection area of its telescopes, the EVN provides excellent sensitivity to weak emission. For IC 310, observations in October and November 2012 at the frequencies 1.7, 5.0, 8.4, and 22.2 GHz were carried out.

The MOJAVE project is a long-term VLBI monitoring program at 15 GHz conducted with the Very Long Baseline Array (VLBA) as a continuation of the VLBA 2 cm survey, for example, Lister et al. (2016)\(^10\). The array consists of ten identical 25 m (in diameter) antennas with a baseline up to 8000 km. IC 310 was included in the target list of MOJAVE in early 2012.

A description of the analysis of the EVN data can be partially found in Aleksić et al. (2014c). More information on the data analysis procedure of the MOJAVE and OVRO data and an extended analysis of these data will be published in a separate paper (Schulz et al., in prep.), which will include additional observations made over a longer period of time that will allow the investigation of possible changes of the jet structure. Only the results of the OVRO observations during the campaign and EVN and MOJAVE flux density measurements are presented here as they are relevant to the study of the multi-band light curve and the SED.

2.6. Additional data

We also consider historical data of IC 310 for the SED from the Wide-Field Infrared Survey Explorer (WISE) and the Two Micron All Sky Survey (2MASS). The AllWISE Source Catalog (Wright et al. 2010) covers a time range from 2010 January to 2010 November, while the 2MASS catalog (Skrutskie et al. 2006) covers from 1997 June to 2001 February. The data were de-reddened using the absorption column derived from historical data of IC 310 for the SED and MOJAVE flux density measurements are presented here as they are relevant to the study of the multi-band light curve and the SED.

3. Results

In this section we present the results from the MWL observation starting with the highest energies.

3.1. MAGIC results

During the period 2012 November to 2013 January (MJD 56 245.0–56 309.1), IC 310 was detected by MAGIC using data (excluding the flare data of MJD 56 244.0) over an effective time (observation time minus dead time) $t_{\text{eff}} = 35.3$ h with a significance of $5.22\sigma$ above 300 GeV. This low significance measured over a rather long time span indicates a low flux state after the flare. Here we have excluded the flare data from the data selection for two reasons. Firstly, to test the detection of the object outside of the flaring state and secondly, because a large part of the observations used for the MWL SED, for example, in X-rays, was performed at a time not simultaneously with the TeV flare.

The energy spectrum $\frac{dN}{dE}$ between 82 GeV and 2.1 TeV during the campaign from 2012 November to 2013 January (Fig. 1), excluding the flare data, can be described with the power-law function:

$$dN = f_0 \left( \frac{E}{1 \text{ TeV}} \right)^{-\Gamma} \times 10^{-12} \text{ cm}^{-2} \text{s}^{-1} \text{ TeV}^{-1}$$

(1)

with a flux normalization $f_0 = (3.12 \pm 0.91_{\text{stat}} \pm 0.34_{\text{syst}}) \times 10^{-13} \text{ cm}^{-2} \text{s}^{-1}$ at 1 TeV and a photon spectral index of $\Gamma = (2.36 \pm 0.30_{\text{stat}} \pm 0.15_{\text{syst}})$. The normalization energy of 1 TeV was fixed and selected for easier comparison with previous measurements. As simultaneous Swift-XRT and UVOT data are only available for the 2012 November and December observations, we also calculated a MAGIC spectrum for the time period 2012 November to December in the same energy range. The resulting spectrum agrees, within the errors, with the spectrum calculated for the entire campaign. Thus, in the subsequent sections we only show and discuss the spectrum for the entire campaign.

We further investigated the change in the spectrum at different flux states by comparing our results with previous measurements. As simultaneous Swift-XRT and UVOT data are only available for the 2012 November and December observations, we also calculated a MAGIC spectrum for the time period 2012 November to December in the same energy range. The resulting spectrum agrees, within the errors, with the spectrum calculated for the entire campaign. Thus, in the subsequent sections we only show and discuss the spectrum for the entire campaign.

We further investigated the change in the spectrum at different flux states by comparing our results with previous measurements. As simultaneous Swift-XRT and UVOT data are only available for the 2012 November and December observations, we also calculated a MAGIC spectrum for the time period 2012 November to December in the same energy range. The resulting spectrum agrees, within the errors, with the spectrum calculated for the entire campaign. Thus, in the subsequent sections we only show and discuss the spectrum for the entire campaign.

In Fig. 4, we present for all temporally non-overlapping data the photon spectral index versus the integrated flux (overlapping
Table 2. Results of power-law spectra measured with MAGIC during different periods.

<table>
<thead>
<tr>
<th>State</th>
<th>Comment</th>
<th>Energy range [TeV]</th>
<th>$f_0 \pm f_{\text{stat}} \pm f_{\text{syst}} \times 10^{-12}$ [TeV$^{-1}$ cm$^{-2}$ s$^{-1}$]</th>
<th>$\Gamma \pm \Gamma_{\text{stat}} \pm \Gamma_{\text{syst}}$</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>high state 2009/2010</td>
<td>observed</td>
<td>0.12–8.1</td>
<td>4.28 ± 0.21 ± 0.73</td>
<td>1.96 ± 0.10 ± 0.20</td>
<td>Aleksić et al. (2014a)</td>
</tr>
<tr>
<td>low state 2009/2010</td>
<td>observed</td>
<td>0.12–8.1</td>
<td>0.608 ± 0.037 ± 0.11</td>
<td>1.95 ± 0.12 ± 0.20</td>
<td>Aleksić et al. (2014a)</td>
</tr>
<tr>
<td>flare Nov. 2012</td>
<td>observed</td>
<td>0.07–8.3</td>
<td>17.7 ± 0.9 ± 2.1</td>
<td>1.90 ± 0.04 ± 0.15</td>
<td>Aleksić et al. (2014c)</td>
</tr>
<tr>
<td>flare period Nov. 2012 I</td>
<td>observed</td>
<td>0.07–4.0</td>
<td>6.4 ± 0.8 ± 0.7</td>
<td>2.15 ± 0.10 ± 0.15</td>
<td>this work</td>
</tr>
<tr>
<td>flare period Nov. 2012 II</td>
<td>observed</td>
<td>0.07–9.5</td>
<td>13.5 ± 0.9 ± 1.5</td>
<td>1.96 ± 0.06 ± 0.15</td>
<td>this work</td>
</tr>
<tr>
<td>flare period Nov. 2012 III</td>
<td>observed</td>
<td>0.07–4.0</td>
<td>37.5 ± 4.2 ± 4.1</td>
<td>1.63 ± 0.11 ± 0.15</td>
<td>this work</td>
</tr>
<tr>
<td>flare period Nov. 2012 IV</td>
<td>observed</td>
<td>0.07–9.5</td>
<td>44.2 ± 2.1 ± 4.9</td>
<td>1.51 ± 0.06 ± 0.15</td>
<td>this work</td>
</tr>
<tr>
<td>flare period Nov. 2012 V</td>
<td>observed</td>
<td>0.07–9.5</td>
<td>27.5 ± 2.3 ± 3.0</td>
<td>1.85 ± 0.08 ± 0.15</td>
<td>this work</td>
</tr>
<tr>
<td>Nov. 2012–Jan. 2013</td>
<td>observed</td>
<td>0.08–2.1</td>
<td>0.31 ± 0.09 ± 0.03</td>
<td>2.36 ± 0.30 ± 0.15</td>
<td>this work</td>
</tr>
<tr>
<td>Nov. 2012–Jan. 2013</td>
<td>intrinsic</td>
<td>0.08–2.1</td>
<td>0.37 ± 0.11 ± 0.04</td>
<td>2.26 ± 0.30 ± 0.15</td>
<td>this work</td>
</tr>
</tbody>
</table>

Fig. 2. Division of the MAGIC data taken during the night of 2012 November 12–13 into data sub-sets according to different flux states. The light curve data points are taken from Aleksić et al. (2014c). Vertical lines and colored boxes indicate the boundaries for the different flux periods used for the investigation of the spectral variability. The time intervals related to the above-mentioned periods are reported in Table 1.

Fig. 3. Measured spectral energy distributions from different time periods during the night of the flare 2012 November 12–13 obtained by MAGIC. The time periods are given in Table 1 and indicated with lines in Fig. 2. The same color scheme as in Fig. 2 is used.

Fig. 4. Power-law index of VHE spectra as a function of the VHE flux above 300 GeV measured by MAGIC. The photon index values, which are not corrected for EBL absorption, are listed in Table 2. The color scheme is the same as the one used in Fig. 2 and in Fig. 3. In addition, the result for the multi-wavelength campaign is shown in blue, and the historical measurements from Aleksić et al. (2014a) are shown in black. The solid and dashed lines represent a constant and a linear fit, respectively.

The mean integrated flux over the entire period was measured to be $F_{\text{mean}} = (1.59 \pm 0.29) \times 10^{-12}$ cm$^{-2}$ s$^{-1}$ above 300 GeV when excluding the data from the 2012 November flare. This is ~40 times lower than the mean integrated flux of $(6.08 \pm 0.29) \times 10^{-11}$ cm$^{-2}$ s$^{-1}$ reported for the 2012 November flare in Aleksić et al. (2014c). Due to the faint emission, a monthly light curve is computed. The light curve is calculated assuming a simple power-law distribution with a photon index of $\Gamma = 2.4$. For the data during the flare, a different photon index, $\Gamma = 2.0$, was used. The monthly calculated light curve is previous measurements (Aleksić et al. 2014a) and from the data presented here. A constant fit to the data points in Fig. 4 reveals a $\chi^2$/d.o.f. of 52.5/7, thus a low probability for being constant of $4.6 \times 10^{-9}$. A higher probability can be obtained with a linear function which yields a $\chi^2$/d.o.f. of 7.0/6 and a probability of 0.32.
The Fermi measured light curve is shown in Fig. 9. Only upper limits of Fermi January 31 (MJD 56 323), IC 310 could not be detected with days are given in Table 3.

The flux is found from month to month. Results from individual Campaign from 2012 November 01 to 2013 January 31 and an energy range of 2–10 keV, the photon index, and $N_{\text{H}}$ can be found in Table 4.

The temporal evolution of the flux in the energy range 2–10 keV, the photon index, and the column density $N_{\text{H}}$ in 2012 November to December during the campaign is presented in Fig. 5. The mean energy flux has been measured to be $(0.61 \pm 0.01) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, which is about five times higher than during previous measurements (Aleksić et al. 2014a) and moderately higher (factor of 1.4) than in 2012 January (see Table 4). A fit to the light curve with a constant line reveals a probability of $7.3 \times 10^{-2}$ for a constant energy flux of $(0.58 \pm 0.01) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ ($\chi^2$/d.o.f. = 49.6/11). The observation on MJD 56 280.82 deviates by $\sim 5\sigma$ from this constant energy flux value.

Comparing the light curve with the temporal evolution of the photon index yields evidence for a spectral hardening with increasing energy flux. We fit the photon index versus time with a constant, yielding $\chi^2$/d.o.f. = 45.2/11 (probability of $4.5 \times 10^{-6}$) indicating a change of the photon index from day to day. This evidence is also found when displaying the photon index as a function of the energy flux between 2–10 keV as shown in Fig. 6. A linear fit gives a $\chi^2$/d.o.f. of 14.0/10 (probability of 0.17). Thus, a harder-when-brighter behavior is observed during the campaign. Although spectral and flux variability in the X-ray band were previously reported in Aleksić et al. (2014a), a harder-when-brighter trend for these observations was not found.

The hydrogen column density stayed constant during the campaign ($\chi^2$/d.o.f. = 13.4/11, probability of 0.26 for a constant fit) and is consistent with the Galactic value for IC 310 $1.2 \times 10^{22}$ cm$^{-2}$ from Kalberla et al. (2010) taking into account the large systematic uncertainties ($\sim 30\%$) of the survey. Hence, no conclusions can be drawn on intrinsic photo-absorption during the campaign.

For the investigation of the multi-wavelength SED, all data taken in 2012 November and December were combined to derive an averaged spectrum during the campaign. The result is shown in Fig. 7. It can be well described with a simple absorbed power-law in the range 0.5–10 keV with a hard photon spectral index of $\Gamma = 2.036_{-0.022}^{+0.019}$. This index is comparable within the errors with the index of the averaged spectrum obtained from measurements at the beginning of the year 2012.

From the INTEGRAL data, a $1\sigma$ upper limit is extracted from the variance of the stacked mosaic image at the source position taking into account a photon index of 2.0, which is extrapolated from the Swift–XRT band. This results in an upper limit of the energy flux of $2.9 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ at 110 keV in the energy range 20–200 keV. Assuming a softer photon index of 2.5, the upper limit yields $1.7 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ at 110 keV in the energy range 20–200 keV. For the broadband SED in Fig. 10, we show the $2\sigma$ upper limit calculated for the photon index of 2.0 and multiply it with a factor of 1.5 for the root mean square of the significance map.

The BAT data yield an energy flux of $(3.2 \pm 1.4) \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ for the energy range 20–100 keV and a photon index of $1.8 \pm 1.1$ for the 104-month Swift–BAT survey maps with a signal-to-noise ratio of 1.85$\sigma$. Uncertainties are given at a $90\%$ confidence level. For the broadband SED, we used the energy flux value instead of an upper limit. We applied the criterion of $3\sigma$ for the calculation of energy flux upper limits. But, as three times the $1\sigma$ energy flux uncertainty is smaller than the

### Notes

The dates given in the first column correspond to the day following the observation night. The upper limits were computed with a 95% confidence level.

### Table 3. MAGIC gamma-ray flux measurements from single observations, as well as integrated over months.

<table>
<thead>
<tr>
<th>Data used</th>
<th>MJD start</th>
<th>$t_{\text{obs}}$</th>
<th>$F_{\text{E&gt;300 GeV}}$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>all data (flare excl.)</td>
<td>...</td>
<td>35.3</td>
<td>1.59 ± 0.29</td>
<td></td>
</tr>
<tr>
<td>2012 Nov. (flare excl.)</td>
<td>...</td>
<td>17.9</td>
<td>1.69 ± 0.42</td>
<td></td>
</tr>
<tr>
<td>2012 Dec.</td>
<td>...</td>
<td>7.1</td>
<td>1.88 ± 0.61</td>
<td></td>
</tr>
<tr>
<td>2013 Jan.</td>
<td>...</td>
<td>10.4</td>
<td>(0.61 ± 0.54) &lt; 2.09</td>
<td></td>
</tr>
</tbody>
</table>

### 3.3. X-ray

The light curve measured with Swift–XRT is shown in Fig. 5 and in Fig. 9. An overview of the results – for example, the flux level in the energy range of 2–10 keV, the photon index, and $N_{\text{H}}$ – can be found in Table 4.

The temporal evolution of the flux in the energy range 2–10 keV, the photon index, and the column density $N_{\text{H}}$ in 2012 November to December during the campaign is presented in Fig. 5. The mean energy flux has been measured to be $(0.61 \pm 0.01) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, which is about five times higher than during previous measurements (Aleksić et al. 2014a) and moderately higher (factor of 1.4) than in 2012 January (see Table 4). A fit to the light curve with a constant line reveals a probability of $7.3 \times 10^{-2}$ for a constant energy flux of $(0.58 \pm 0.01) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ ($\chi^2$/d.o.f. = 49.6/11). The observation on MJD 56 280.82 deviates by $\sim 5\sigma$ from this constant energy flux value.

Comparing the light curve with the temporal evolution of the photon index yields evidence for a spectral hardening with increasing energy flux. We fit the photon index versus time with a constant, yielding $\chi^2$/d.o.f. = 45.2/11 (probability of $4.5 \times 10^{-6}$) indicating a change of the photon index from day to day. This evidence is also found when displaying the photon index as a function of the energy flux between 2–10 keV as shown in Fig. 6. A linear fit gives a $\chi^2$/d.o.f. of 14.0/10 (probability of 0.17). Thus, a harder-when-brighter behavior is observed during the campaign. Although spectral and flux variability in the X-ray band were previously reported in Aleksić et al. (2014a), a harder-when-brighter trend for these observations was not found.

The hydrogen column density stayed constant during the campaign ($\chi^2$/d.o.f. = 13.4/11, probability of 0.26 for a constant fit) and is consistent with the Galactic value for IC 310 $(0.12 \times 10^{22}$ cm$^{-2}$) from Kalberla et al. (2010) taking into account the large systematic uncertainties ($\sim 30\%$) of the survey. Hence, no conclusions can be drawn on intrinsic photo-absorption during the campaign.

For the investigation of the multi-wavelength SED, all data taken in 2012 November and December were combined to derive an averaged spectrum during the campaign. The result is shown in Fig. 7. It can be well described with a simple absorbed power-law in the range 0.5–10 keV with a hard photon spectral index of $\Gamma = 2.036_{-0.022}^{+0.019}$. This index is comparable within the errors with the index of the averaged spectrum obtained from measurements at the beginning of the year 2012.

From the INTEGRAL data, a $1\sigma$ upper limit is extracted from the variance of the stacked mosaic image at the source position taking into account a photon index of 2.0, which is extrapolated from the Swift–XRT band. This results in an upper limit of the energy flux of $2.9 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ at 110 keV in the energy range 20–200 keV. Assuming a softer photon index of 2.5, the upper limit yields $1.7 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ at 110 keV in the energy range 20–200 keV. For the broadband SED in Fig. 10, we show the $2\sigma$ upper limit calculated for the photon index of 2.0 and multiply it with a factor of 1.5 for the root mean square of the significance map.

The BAT data yield an energy flux of $(3.2 \pm 1.4) \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ for the energy range 20–100 keV and a photon index of $1.8 \pm 1.1$ for the 104-month Swift–BAT survey maps with a signal-to-noise ratio of 1.85$\sigma$. Uncertainties are given at a $90\%$ confidence level. For the broadband SED, we used the energy flux value instead of an upper limit. We applied the criterion of $3\sigma$ for the calculation of energy flux upper limits. But, as three times the $1\sigma$ energy flux uncertainty is smaller than the
Table 4. Swift-XRT X-ray spectral measurements from observations in 2012 January and 2012 November to December.

<table>
<thead>
<tr>
<th>Obs. ID</th>
<th>MJD start</th>
<th>Exp.</th>
<th>$F_{2-10\text{keV}} \times 10^{-11}$ [erg s$^{-1}$ cm$^{-2}$]</th>
<th>$\Gamma$</th>
<th>$N_H$ [10$^{22}$ cm$^{-2}$]</th>
<th>$\chi^2$/d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012 Jan.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>00032264001</td>
<td>55952.65</td>
<td>2989</td>
<td>0.40 ± 0.04</td>
<td>2.07±0.10</td>
<td>0.10±0.06</td>
<td>18.9/17</td>
</tr>
<tr>
<td>00032264003</td>
<td>55953.58</td>
<td>2885</td>
<td>0.37 ± 0.03</td>
<td>2.18±0.12</td>
<td>0.18±0.05</td>
<td>11.7/15</td>
</tr>
<tr>
<td>00032264004</td>
<td>55954.12</td>
<td>2742</td>
<td>0.48±0.09</td>
<td>2.10±0.15</td>
<td>0.14±0.04</td>
<td>9.3/17</td>
</tr>
<tr>
<td>00032264005</td>
<td>55955.12</td>
<td>3094</td>
<td>0.48±0.04</td>
<td>2.13±0.06</td>
<td>0.12±0.04</td>
<td>24.5/22</td>
</tr>
<tr>
<td>00032264006</td>
<td>55956.14</td>
<td>1504</td>
<td>0.45 ± 0.05</td>
<td>2.03±0.09</td>
<td>0.11±0.05</td>
<td>14.6/8</td>
</tr>
<tr>
<td>2012 Nov.–Dec.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>00032264007</td>
<td>56245.67</td>
<td>4977</td>
<td>0.64 ± 0.04</td>
<td>1.93±0.05</td>
<td>0.126±0.024</td>
<td>37.3/38</td>
</tr>
<tr>
<td>00032264008</td>
<td>56253.09</td>
<td>3984</td>
<td>0.61 ± 0.04</td>
<td>2.13±0.05</td>
<td>0.118±0.025</td>
<td>43.8/36</td>
</tr>
<tr>
<td>00032264009</td>
<td>56253.98</td>
<td>3968</td>
<td>0.69 ± 0.04</td>
<td>1.90±0.06</td>
<td>0.061±0.024</td>
<td>32.9/31</td>
</tr>
<tr>
<td>00032264010</td>
<td>56255.70</td>
<td>3991</td>
<td>0.49 ± 0.04</td>
<td>2.17±0.06</td>
<td>0.151±0.030</td>
<td>22.3/23</td>
</tr>
<tr>
<td>00032264011</td>
<td>56273.95</td>
<td>1983</td>
<td>0.56 ± 0.06</td>
<td>2.02±0.09</td>
<td>0.16±0.05</td>
<td>7.3/11</td>
</tr>
<tr>
<td>00032264012</td>
<td>56275.88</td>
<td>3891</td>
<td>0.59 ± 0.04</td>
<td>1.92±0.07</td>
<td>0.116±0.029</td>
<td>29.6/28</td>
</tr>
<tr>
<td>00032264013</td>
<td>56276.81</td>
<td>3878</td>
<td>0.66 ± 0.04</td>
<td>1.96±0.10</td>
<td>0.140±0.027</td>
<td>34.3/31</td>
</tr>
<tr>
<td>00032264014</td>
<td>56277.81</td>
<td>3878</td>
<td>0.65 ± 0.04</td>
<td>1.95±0.08</td>
<td>0.13±0.04</td>
<td>23.2/30</td>
</tr>
<tr>
<td>00032264015</td>
<td>56278.82</td>
<td>3660</td>
<td>0.62 ± 0.04</td>
<td>2.11±0.10</td>
<td>0.171±0.029</td>
<td>37.7/29</td>
</tr>
<tr>
<td>00032264016</td>
<td>56279.82</td>
<td>3864</td>
<td>0.55 ± 0.04</td>
<td>2.18±0.06</td>
<td>0.173±0.030</td>
<td>23.1/30</td>
</tr>
<tr>
<td>00032264017</td>
<td>56280.82</td>
<td>3856</td>
<td>0.44 ± 0.03</td>
<td>2.28±0.05</td>
<td>0.149±0.028</td>
<td>47.3/28</td>
</tr>
<tr>
<td>00032264018</td>
<td>56281.82</td>
<td>3844</td>
<td>0.58 ± 0.04</td>
<td>1.99±0.07</td>
<td>0.127±0.024</td>
<td>31.9/28</td>
</tr>
</tbody>
</table>

Notes. Energy fluxes in the range 2–10 keV were determined by a simple absorbed power-law fit. The photon index $\Gamma$ is defined following $F \propto E^{-\Gamma}$. $N_H$ denotes the absorption with an equivalent column of hydrogen.
Fig. 6. Power-law index of X-ray spectra as a function of the energy flux (2–10 keV) measured by Swift-XRT. The dashed and solid lines represent a fit to the data with a constant and a linear function, respectively. Red points show the results from individual pointing during the MWL campaign. Additionally, gray points represent the 2012 January data.

Fig. 7. Averaged spectral energy distribution from Swift-XRT observations from 2012 November to December. The measured spectrum is shown with gray points and is fit with an absorbed power-law function (gray lines). Fit results are given in Table 4. The de-absorbed spectrum is shown with black points and black lines. Top panel: resulting spectra in the energy range 0.5–10 keV. Bottom panel: residual of the observed spectrum.

To interpret and model the broadband SED, mean flux densities for each frequency were calculated from the data taken in 2012 November 12 to 2013 February 02 (MJD 56 243–56 325) is consistent with a constant flux density of \( (9.08 \pm 0.04) \) mJy \( (\chi^2 / \text{d.o.f.} = 5.3 / 17, \text{probability of } 0.99) \). As no further historical monitoring in the \( R \)-band was conducted for IC 310, the flux density cannot be compared with other measurements.

An overview of the observations from 2012 November to December by Swift-UVOT is given in Table 5 together with the 2012 January measurements. The results show no significant variability for any of the filters (Fig. 8). A constant fit to the 2012 November to December data revealed no variability for \( B, U, V, UVW1 \) with a fit probability of 0.98, 0.99, 0.95, and 0.98, respectively. Smaller fit probabilities were obtained for the \( UVM2 \) and \( UVW2 \) measurements (0.26 and 0.03). Comparing the measurements in 2012 January and 2012 November-December, only at the highest frequencies (\( UVM2 \) and \( UVW2 \)) the mean flux densities from late 2012 are not compatible within the errors with the measurements in early 2012.

To interpret and model the broadband SED, mean flux densities for each frequency were calculated from the data taken in 2012 November to December. The values obtained are listed in Table 6. The SED in Fig. 10 shows the observed and dereddened KVA and mean data from Swift-UVOT using the absorption measurement from Swift-XRT.

energy flux measurement, we did not classify the energy flux as an upper limit.

### 3.4. Optical and UV

The KVA \( R \)-band optical light curve is shown in Fig. 9 and does not show any signs of variability. The light curve in the time range of 2012 November 12 to 2013 February 02 (MJD 56 243–56 325) is consistent with a constant flux density of \( (9.08 \pm 0.04) \) mJy \( (\chi^2 / \text{d.o.f.} = 5.3 / 17, \text{probability of } 0.99) \). As no further historical monitoring in the \( R \)-band was conducted for IC 310, the flux density cannot be compared with other measurements.

An overview of the observations from 2012 November to December by Swift-UVOT is given in Table 5 together with the 2012 January measurements. The results show no significant variability for any of the filters (Fig. 8). A constant fit to the 2012 November to December data revealed no variability for \( B, U, V, UVW1 \) with a fit probability of 0.98, 0.99, 0.95, and 0.98, respectively. Smaller fit probabilities were obtained for the \( UVM2 \) and \( UVW2 \) measurements (0.26 and 0.03). Comparing the measurements in 2012 January and 2012 November-December, only at the highest frequencies (\( UVM2 \) and \( UVW2 \)) the mean flux densities from late 2012 are not compatible within the errors with the measurements in early 2012.

To interpret and model the broadband SED, mean flux densities for each frequency were calculated from the data taken in 2012 November to December. The values obtained are listed in Table 6. The SED in Fig. 10 shows the observed and dereddened KVA and mean data from Swift-UVOT using the absorption measurement from Swift-XRT.
indicated in the legend. All data are de-reddened using Swift.

Fig. 8. Multi-frequency energy flux light curve of IC 310 obtained from Swift-UVOT observations. The markers for the different frequencies are indicated in the legend. All data are de-reddened using $N_{	ext{H}} = 0.13 \times 10^{22} \text{ cm}^{-2}$. To show the results from the 2012 January as well as the 2012 November to December observations simultaneously, the x-axis has been interrupted, as indicated by the diagonal lines. We note that the y-axis uses a logarithmic scale.

3.5. Radio band

The light curve at 15 GHz obtained by the OVRO monitoring program is shown in Fig. 9. From a fit of the data points from 2012 October 30 to December 23 (MJD 56 230–56 284) to a constant, a mean flux density of $(0.151 \pm 0.002) \text{ mJy}$ is measured with a y$^2$/d.o.f. of 31.1/13 and rather low probability of 0.003 for being constant.

From the EVN and MOJAVE data, the core and total flux density were calculated and included in Fig. 10. The estimated uncertainties for the EVN flux density measurements at 1.7, 5.0, 8.4 GHz are 10% and for 22 GHz, 15%. For the MOJAVE data we adopted an uncertainty of 5% for the total flux density (Lister & Homan 2005). We use the results from the 5.0 GHz observation taken from Aleksić et al. (2014c).

4. Discussion

In the following we discuss the results in terms of multi-frequency flux variability and interpret the broadband SED.

4.1. Multi-frequency flux variability

The combined multi-wavelength light curve is shown in Fig. 9. An exceptional TeV flare was found by MAGIC in November 2012. IC 310 remained active at VHE even after the flare. Only Fermi-LAT, Swift-BAT and partially KVA observed simultaneous to MAGIC on 2012 November 12–13. However, IC 310 could not be detected with the first two instruments during the TeV flare and the optical emission observed by KVA is dominated by the host galaxy.

Contemporaneous measurements starting after the flare indicated a high and variable state of the object in the soft X-ray range. This marks the first time that a contemporaneous measurement of the VHE and the soft X-ray flux is reported for IC 310.

Conclusions on a correlation between the two bands should be drawn with caution because historical simultaneous measurements in both energy ranges are missing. However, considering the harder-when-brighter trend in the VHE and X-ray bands reported in Figs. 4 and 6, one can speculate that these two bands may be connected.

A harder-when-brighter behavior is frequently observed for other sources such as high-frequency peaked BL Lac (HBL) objects (Pan et al. 1998; Giommi et al. 2000; Aleksić et al. 2013, 2015; Furniss et al. 2015; Kapanadze et al. 2016; Ahnen et al. 2016a; Baloković et al. 2016). Here, the increase of the X-ray and VHE flux is combined with a hardening of the spectrum. This is consistent with the synchrotron self-Compton (SSC) mechanism, see Sect. 4.2.2. The first hump in the SED moves toward higher frequencies. The same happens for the second hump, as during a higher flux state the synchrotron photons in the low energy band are seeds for the inverse-Compton emission observed in the high-energy bands. If such a behavior is observed for a blazar with a small viewing angle, one should expect the same also for radio galaxies. This would be in line with the unified model by Urry & Padovani (1995). We note that X-ray data from other misaligned blazars (e.g., NGC 1275) often show complex emission, with a non-pure power-law and extended jet emission or X-ray emission of the filaments (Fabian et al. 2011).

The optical light curve does not show a significantly higher flux or variability. The lack of optical variability is consistent with the result of the SED modeling (see Sect. 4.2.3). The optical-infrared emission is ascribed entirely to the host galaxy, while the variable jet emission starts to dominate in the far-UV and soft X-ray band. The radio light curve indicates weak variability. As radio flares combined with an appearance of a new radio component in the VLBI images are sometimes found a few months after a gamma-ray flare Acciari et al. (2009), the time period covered here is too short to draw conclusions.

Generally, the VHE flare might be interpreted as an injection of fresh electrons and positrons into the SSC emission region. One possible origin of these particles could be the electro-magnetic cascades in the gap region of magnetospheric models resulting in an increased number of $e^+e^−$ pairs (Beskin et al. 1992; Rieger & Mannheim 2000; Neronov & Aharonian 2007; Levinson & Rieger 2011). Such a model has been used to explain the flaring activity from Mrk 87 by Levinson & Rieger (2011) as well as the minute timescale variability of the gamma-ray emission of IC 310 at the beginning of the MWL campaign reported by Aleksić et al. (2014c) and critically examined in Hirotani & Pu (2016). Since the magnetic field is assumed to be along the jet axis, these particles should then move along the jet and maybe also into the emission region that we observed after the flare. This could cause a higher flux in the X-ray regime as well as at VHE. We note that the quiescent state of IC 310 might be undetectable with MAGIC as sometimes IC 310 could not be detected over a long observation time (Aleksić et al. 2012). Furthermore, these fresh particles moving along the jet could also explain a general activity in the radio band.
Fig. 9. Multi-wavelength light curve of IC 310 between 2012 November and 2013 January. The vertical gray dashed line indicates the day of the TeV flare. The horizontal gray dashed lines are the fits to the data with a constant. From top to bottom: MAGIC monthly flux measurements above 300 GeV. In addition, for 2013 January a flux 95% confidence level upper limit is calculated. The gray lines indicate the individual days when observations were performed with MAGIC. We note that the y-axis uses a logarithmic scale. Fermi-LAT above 1 GeV, blue lines indicate the arrival times of gamma-ray event candidates. Swift-XRT fluxes between 2–10 keV. R-band flux measurements by KVA (not corrected for the contribution of the host galaxy). OVRO fluxes at 15 GHz.

4.2. Modeling of the spectral energy distribution

4.2.1. Simultaneity of the data

Due to the variable behavior of IC 310 in some frequency bands (Aleksić et al. 2014a,c), SED fitting requires simultaneous data. In the VHE regime, the emission of IC 310 after the flare was rather faint, but still detectable over a long time range spanning over three months. Therefore, we calculated one spectrum over the entire observation time. For the SED, one averaged spectrum from the Swift-XRT observation was calculated. In the high energy range, the Fermi-LAT measurements are covering the time period from 2012 November 1 to 2013 January 31. The HE data is contemporaneous to the MAGIC and Swift-XRT/UVOT observations. Furthermore, we included the archival spectra from the 3FGL (Acero et al. 2015) and 2FHL catalogs (Ackermann et al. 2016). The former was recorded from 2008 August–2012 July and does not cover the time of the campaign, whereas the 2FHL outlasts the campaign. The results from BAT were extracted from the long-term 104-month survey running from 2004 December to 2013 August, and are taken as an average measurement. INTEGRAL observations cover the time range from 2012 August to 2013 February and therefore are quasi-simultaneous. The optical data from KVA were coordinated with the MAGIC observations and are therefore simultaneous to those. The radio data from EVN and MOJAVE have been included on a quasi-simultaneous basis. To
The SED of a jet-dominated radio-loud AGN can be explained by non-thermal emission of accelerated particles. In the shock-in-jet model (Blandford & Königl 1979), these particles are accelerated at shock waves in the jet which can originate, for example, from density fluctuations of the plasma. The low-energy emission of the double-humped SED of radio-loud AGNs is explained by synchrotron radiation of the electrons and positrons due to the magnetic fields in the jets. In contrast, the origin of the higher energy hump is still a matter of debate. Leptonic (inverse) Compton scattering (Marscher & Gear 1985; Maraschi et al. 1992; Bloom & Marscher 1996), and hadronic – for example, proton synchrotron (Mannheim 1993b; Mücke et al. 2003) and neutral pion decay initiated electromagnetic cascades (Mannheim 1993a) – processes can lead to the emission observed at higher frequencies. As shown in Aleksić et al. (2014c), this shock-in-jet model cannot explain the fast TeV flare in 2012 November.

As mentioned in Sect. 4.1, freshly injected electrons and positrons may result from electro-magnetic cascades inside a gap region of a pulsar-like magnetosphere surrounding the central black hole. The acceleration of the particles due to the huge electric potential in the gap and emission via inverse-Compton and curvature radiation can explain the flaring behavior as reported in Aleksić et al. (2014c). However, after some time, the gap short-circuited because the charge density reaches the Goldreich-Julian charge density and the cascading stops. The particles may move in the direction of the jet.

We adopt the single-zone SSC model by (Krawczynski et al. 2004) to model the broadband SED. The model consists of the following parameters: the bulk Lorentz factor $\Gamma_b$, the viewing angle $\theta$, the magnetic field $B$, the radius of the emission region $R$, the electron energy density $U_e$, the ratio $\eta$ of the electron energy density to the magnetic field energy density $U_B$, the minimal energy and the maximal energy of the electrons $E_{\text{min}}$ and $E_{\text{max}}$, the break energy $E_{\text{break}}$, and the spectral indices $p_1$ (d$N$/d$E \propto E^{-p_1}$), $E$ is the electron energy in the jet frame). In this model it is assumed that the electrons follow a broken power-law energy spectrum with the indices $p_1$ for the energies $E_{\text{min}}$ to $E_{\text{break}}$ and $p_2$ for $E_{\text{break}}$ to $E_{\text{max}}$.

We assume a viewing angle of $10^\circ \lesssim \theta \lesssim 20^\circ$ as found by Aleksić et al. (2014c). For this range of viewing angles, a rather low bulk Lorentz factor is necessary to enable having at least a...
moderate Doppler boosting. Here, we use $\Gamma_b = 5$. We note that the models applied to the data are only two possibilities, one for $\theta = 10^\circ$ and one for $\theta = 20^\circ$; generally, a large degeneracy of parameters exists (Ahnen et al. 2016b).

In addition to the SSC model, a template SED for a galaxy of morphology type S0 (Polletta et al. 2007) is added to account for the strong dominance of the host galaxy in the infrared to UV range as observed from the S0-type galaxy IC 310 (de Vaucouleurs et al. 1991). This is the first time that both regimes have been measured simultaneously, so one cannot make a statement concerning the occurrence of a simultaneous low and high state in both bands.

The measured SED of IC 310 seems to follow a simple, featureless double-hump structure besides the host galaxy emission, as seen from blazars. A single-zone SSC model is able to explain the broadband emission in general, though it is not possible to reproduce the flux densities of the VLBI core measurements which likely comprise additional radio emission from other regions.

### 4.2.3. Results

The broadband SED is shown in Fig. 10. Apart from the radio telescopes, the angular resolution of all other instruments used in this paper is a limitation to study a jetted object such as IC 310. Detailed radio observations do not indicate, for example, lobe emission (Sijbring & de Bruyn 1998; Kadler et al. 2012). Moreover, deep X-ray measurements show a mostly point-like emission positionally consistent with the bright radio core (Dunn et al. 2010). Therefore, when modeling the broadband SED, we consider that all emission is coming from around the central region of the AGN.

The measured SED of IC 310 seems to follow a simple, featureless double-hump structure besides the host galaxy emission, as seen from blazars. A single-zone SSC model is able to explain the broadband emission in general, though it is not possible to reproduce the flux densities of the VLBI core measurements which likely comprise additional radio emission from other regions. The radio and X-ray data suggest a broad synchrotron emission hump which can be explained with a large maximal Lorentz factor of the particles. This agrees with the second hump peaking in the GeV range or even higher. However, it is difficult to fit the 3FGL, 2FHL, and low-state MAGIC data simultaneously with an SSC model due to the broadness of the second hump. The SSC model curves are, however, consistent with the upper limits in the GeV band calculated for this campaign.

The parameters of the SSC models used for the magnetic field, the radius of the emission region, and the necessary Lorentz factors of the particles are in agreement with the constraints from the magnetospherical model used to explain the emission from the TeV flare (Aleksić et al. 2014c). Here, we assume that the emission region is caused by a cloud formed out of the particles created due to the cascading in the gap region during the flaring period. This blob moves away from the center of the AGN in the direction of a conical jet with a distance $d$ corresponding to a travel time of 1–2 months. Here, the magnetic field strength reduces from the values inferred from Levinson & Rieger (2011) to the values used in the SSC models from this work, assuming the dependence of $B(d) \sim d^{-1}$ (Konigl 1981; Lobanov 1998). Furthermore, assuming a conical geometry, the radius of the emission region increases to $R \sim 10^{15}$ cm, consistent with the values used for the 10$^7$ model. The required energetics of maximal $E_{\text{max}} = 12$ (in units of log10(E/eV)) with a Lorentz factor of the particles of $\sim 10^5$ can be achieved, as even higher values were found by Hirota & Pu (2016). The SSC code of Krawczynski et al. (2004) includes the effect of $\gamma\gamma$-pair production and for both models the optical thickness for $\gamma\gamma$-pair production is low enough for TeV emission to escape.

In the IR-optical-UV range of the SED, the emission is strongly dominated by the host galaxy. The template SED of the S0-type galaxy represents the measured data points very well. An SSC for an elliptical galaxy would have underestimated the contribution in the optical range by one order of magnitude. Instead, the template used suggests a rather strong emission in the IR band due to starburst processes. Unfortunately, NGC 1275 is too bright in the far-infrared and microwave regime, so that the emission from IC 310 could be outshone by NGC 1275 in maps obtained by the Planck satellite.

Notes. Resulting model curves are depicted in Fig. 10.

<table>
<thead>
<tr>
<th>$\Gamma$</th>
<th>$\beta$</th>
<th>$\theta$</th>
<th>$p_1$</th>
<th>$p_2$</th>
<th>$E_{\text{min}}$</th>
<th>$E_{\text{max}}$</th>
<th>$E_{\text{peak}}$</th>
<th>$U_b$</th>
<th>$\eta$</th>
<th>$B$</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5.7</td>
<td>0.1</td>
<td>2.0</td>
<td>3.1</td>
<td>5.7</td>
<td>12.0</td>
<td>10.6</td>
<td>0.21</td>
<td>59.0</td>
<td>0.3</td>
<td>$2.1 \times 10^{15}$</td>
</tr>
<tr>
<td>5</td>
<td>2.5</td>
<td>0.1</td>
<td>2.0</td>
<td>3.1</td>
<td>5.7</td>
<td>12.4</td>
<td>10.8</td>
<td>0.012</td>
<td>30.0</td>
<td>0.1</td>
<td>$3.0 \times 10^{16}$</td>
</tr>
</tbody>
</table>

Notes. Resulting model curves are depicted in Fig. 10.
Finally, we use the broadband SED to determine the mass of the central black hole analogous to Krauß et al. (2016) using the fundamental plane of black hole activity. We assume the X-ray flux of the 2012 November and December data (Table 4), the 5 GHz core flux measurement from EVN and extrapolated the EVN core data with a simple power-law spectrum in order to estimate the 1.4 GHz flux. The extrapolation was done by fitting the spectrum of the 1.7, 5.0, 8.4, and 22.2 GHz core data with a power-law of the form \( dN/dE = (E/E_0)^{-\Gamma} \) with \( E_0 \) being a normalization flux and \( \Gamma_R \) the power-law index. The fitting yields \( \Gamma_R = 0.95 \) and thus a differential flux at 1.4 GHz of \( 1.08 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \). The resulting masses are given in \( \log M_{\text{BH}} (M_\odot) = (7.89 \pm 0.09) \) for the fundamental plane found in Gültekin et al. (2009), (8.4±1.3) for Merloni et al. (2003), (9.2±4) for Körding et al. (2006), for (8.4 ± 2.9) Bonchi et al. (2013), and (8.2 ± 1.0) for Nisbet & Best (2016)\(^{14}\). These values are consistent with \( M_{\text{BH}} = \left(3^{+1}_{-2}\right) \times 10^8 M_\odot \) reported in Aleksić et al. (2014c). Instead, Berton et al. (2015) estimated a mass for IC 310 of one order of magnitude lower than the value estimated in Aleksić et al. (2014c) based on a smaller velocity dispersion used for the \( M_{\text{BH}} - \sigma \) relation. Assuming a smaller mass would somewhat weaken the arguments given in Aleksić et al. (2014c) as the variability timescale then roughly equals the event horizon light crossing time. But the opacity problem as explained in Aleksić et al. (2014c) still remains.

4.2.4. Comparison with misaligned blazars and blazars

The SSC model parameter values reported in this study for IC 310 are similar to those obtained for misaligned blazars, for example, PKS 0625–354, 3C 78 in Fukazawa et al. (2015), Cen A core in Abdo et al. (2010a), M 87 in Abdo et al. (2009b), NGC 1275 in Abdo et al. (2009a) and Aleksić et al. (2014b), and NGC 6251 in Migliori et al. (2011)\(^{15}\). Compared to BL Lac objects, the values for the bulk Lorentz and Doppler factor are lower for IC 310 as well as the other misaligned blazars. This is understandable because the Doppler boosting is weaker as a result of the larger viewing angle. However, to maintain some boosting at larger viewing angles, a smaller bulk Lorentz factor is mandatory. Lower bulk Lorentz factors were also found for gamma-ray blazars in a quiescent state (Ahnen et al. 2016b), but large Lorentz factors are needed to explain the fast variability observed from blazars (Begelman et al. 2008). The radii for the emission region used for IC 310 coincide with the observed variability of the object in the X-ray range after the TeV flare and are comparable to those used for other misaligned blazars. Interestingly, the models for IC 310 show a higher \( \gamma_{\text{break}} = \frac{E_{\text{break}}}{\Delta E} \) similar to the SEDs from PKS 0625–354, 3C 78, and NGC 6251, see Fukazawa et al. (2015) and Migliori et al. (2011). Such high \( \gamma_{\text{break}} \) leads to higher synchrotron peak frequencies (~10^{17} Hz). This is in agreement with the hard spectrum in the soft X-ray and gamma-ray band observed from IC 310. Among the misaligned blazars, IC 310 shows one of the hardest gamma-ray spectra, \( \Gamma_{\text{FGL}} = 1.90 \pm 0.14 \) in the 3FGL (Acero et al. 2015), the hardest in the 2FHL catalog (Ackermann et al. 2016) with \( \Gamma_{\text{FHL}} = 1.34 \pm 0.42 \), and \( \Gamma_{\text{MAGIC}} = 1.8 – 2.4 \) as reported by MAGIC here and in Aleksić et al. (2010, 2014a,c).

5. Summary and conclusions

In this paper we have presented the results from the first multi-wavelength campaign from radio to the VHE range, conducted in 2012 November and 2013 January for the misaligned blazar IC 310. During the campaign, an exceptionally bright VHE flare was detected showing fast flux variability in one night. There is no significant data from the lower energy bands available for that night due to low statistics of all-sky monitors such as Fermi-LAT and Swift-BAT. After the flare, the TeV flux declined rapidly. Through early 2013, only a low but still detectable VHE emission was observed. Compared to previous measurements and combining those with the results reported in this paper, a harder-when-brighter behavior can be inferred. The same behavior is found for the soft X-ray emission during the campaign. The photon spectral index hardens with increasing flux for IC 310, which we report here for the first time. The harder-when-brighter behavior of the X-ray and VHE emission after the TeV flare is consistent with the expectations from a one-zone SSC mechanism.

Other than the variability found in the X-ray band, the multi-wavelength light curve reveals no strong variability after the TeV flare. In the GeV band, no detection with a high significance could be inferred from the Fermi-LAT observations. The same applies to the Swift-BAT observation in the hard X-ray band. The host galaxy dominates completely the optical emission, and hence the optical variability of this object could not be properly evaluated. For the investigation of the variability in the radio band, a larger period and dedicated VLBI monitoring at one frequency is necessary to make further conclusions on the changes of the pc-scale jet after the flare. This will be discussed in a forthcoming paper by Schulz et al. (in prep.).

As previously reported, the TeV flare cannot be explained with standard shock-in-jet models. An alternative suggestion is based on magnetospheric models for AGNs. According to these, charge-depleted regions in AGN-magnetospheres are the birthplaces of the highest energetic particles and electromagnetic cascades. In these cascades, a large number of electrons and positrons are produced which can in principle load the jet, letting a new blob of particles travel along the jet axis. In this paper, we discussed the possibility that this blob can be the emission zone as required in a single-zone SSC model. We have shown that this simple model can explain the broadband SED of IC 310 observed during the campaign. Furthermore, the parameters used for the SSC modeling agree with those obtained for other gamma-ray loud misaligned blazars.

Acknowledgements. The authors thank M. Dauer, I. Kreykenbohm, S. Richter, A. Shukla, F. Spanier, and M. Weidinger for the support during the preparation of observational proposals or discussion. 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 financial support of the German BMBF and MPG, the Italian INFN and INAF, the Swiss National Fund SNF, the ERDF under the Spanish MINECO (FPA2015-69818-P, FPA2012-36668, FPA2015-68278-P, FPA2015-69210-C6-2-R, FPA2015-69210-C6-4-R, FPA2015-69210-C6-6-R, AYA2013-47447-C3-1-P, AYA2015-71042-P, ESP2015-71662-C2-2-P, CSD2009-00604), and the Japanese JSPS and MEXT is gratefully acknowledged. This work was also supported by the Spanish Centro de Excelencia “Severo Ochoa” SEV-2012-0234 and SEV-2015-0545, and Unidad de Excelencia “María de Maeztu” MDM-2014-0369, by grant 268740 of the Academy of Finland, by the Croatian Science Foundation (Project 09/RZ) and the University of Rijeka Project 13.12.1.3.02, by the DFG Collaborative Research Centers SFB823/C4 and SFB876/C3, and by the Polish MNiSW grant 745/N-HESS-MAGIC/2010/0. The Fermi-LAT Collaboration acknowledges generous ongoing support from a number of agencies and institutes that have supported both the development and the operation of the LAT as well as scientific data analysis. These include the National Aeronautics and Space Administration and the Department of Energy in the United States, the Commissariat à l’Énergie Atomique and the Centre National de la Recherche Scientifique/Institut National de Physique Nucléaire et de Physique