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FACT - Highlights from more than Eight Years of Unbiased TeV Monitoring

Daniela Dorner,[a,*] **A. Arbet-Engels,**[b] **D. Baack,**[c] **M. Balbo,**[d] **A. Biland,**[b] **T. Bretz,**[b,e] **J. Buss,**[c] **L. Eisenberger,**[a] **D. Elsaesser,**[c] **D. Hildebrand,**[b] **R. Iotov,**[a] **A. Kalenski,**[a] **K. Mannheim,**[a] **A. Mitchell,**[b] **D. Neise,**[b] **M. Noethe,**[c] **A. Paravac,**[a] **W. Rhode,**[c] **B. Schleicher,**[a] **V.Sliusar**[d] **and R. Walter**[d]

[a] *Universität Würzburg, Institut für Theoretische Physik und Astrophysik, Würzburg, Germany*
[b] *ETH Zurich, Institute for Particle Physics and Astrophysics, Zurich, Switzerland*
[c] *TU Dortmund, Experimental Physics 5, Dortmund, Germany*
[d] *University of Geneva, Department of Astronomy, Versoix, Switzerland*
[f] *also at: III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany*

E-mail: dorner@astro.uni-wuerzburg.de

The First G-APD Cherenkov Telescope (FACT) has been monitoring blazars at TeV energies for more than eight years. Using solid state photo sensors and performing robotic operations results in a maximized duty cycle of the instrument and minimized observational gaps, providing an unprecedented data sample of more than 14700 hours of physics data. With an unbiased observing strategy, a small sample of sources is monitored. Results of an automatic quick-look analysis are published with low latency on an open-access website. Since 2014, close to 150 alerts including 11 astronomer's telegrams have been issued triggering target-of-opportunity observations and a variety of multi-wavelength studies.

In 2016, FACT alerted MAGIC to a high state of 1ES 2344+51.4. The combined observations revealed a renewed extreme behaviour of the source. Thanks to target-of-opportunity observations triggered by FACT and preplanned joint campaigns, several rich datasets with combined observations with *INTEGRAL*, *XMM-Newton* and *AstroSAT* are available for Mrk 421. Furthermore, dedicated campaigns each observing season provide multi-wavelength light curves and spectral energy distributions for the brightest blazars.

The unprecedented, unbiased TeV data sample also provides the unique chance to study the duty cycle and the long-term spectral and temporal behaviour of the sources, including the search for periodic signals. Studying the long-term variability of Mrk 421 and Mrk 501 in the multi-wavelength context, correlations of different wavelengths are investigated searching for delays.

In this presentation, selected highlights from more than eights years of monitoring will be summarized, including results from deep multi-instrument campaigns and long-term studies.

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1. Introduction

This proceeding summarizes the observations by the First G-APD Cherenkov Telescope (FACT) over eight years. First, the instrument will be introduced and its observation strategy discussed. Next, the results from its monitoring program as well as follow-up observations will be summarized.

1.1 First G-APD Cherenkov Telescope

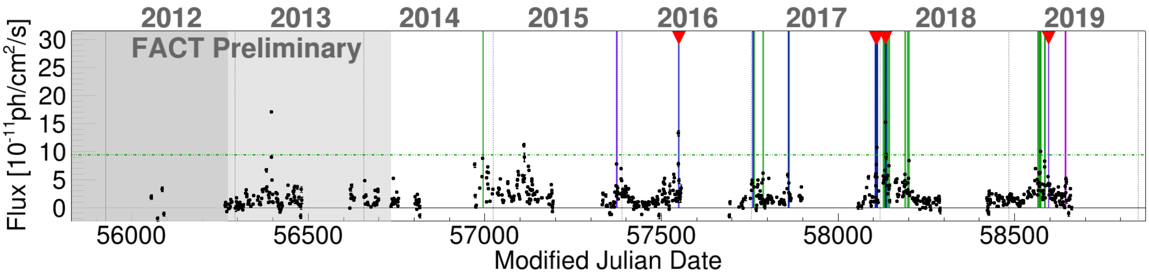
The First G-APD Cherenkov Telescope (FACT) is an imaging air-Cherenkov telescope (IACT) with a 9.5 m^2 mirror located in the Observatorio del Roque de los Muchachos (ORM) in Spain. The major goals of the instrument were the proof-of-principle for Geiger-mode avalanche photodiodes (G-APDs, aka SiPM) in Cherenkov astronomy and the long-term monitoring of bright TeV blazars [1]. Thanks to FACT, using SiPMs in Cherenkov astronomy has become state of the art, nicely illustrated by the usage of these photosensors in the small-size telescopes of the Cherenkov Telescope Array (CTA) [2, 3] and the plans to build a SiPM upgrade for the camera of the large-size telescope (LST) [4, 5]. Also the design aiming for robotic operation provides useful experience for CTA. FACT is operational since October 2011 and remote operation started in summer 2012. Automatizing the operation allowed not only for a stable performance but also a high data taking efficiency [6]. Both are very beneficial for a consistent and continuous monitoring.

1.2 Monitoring Program and Observing Strategy

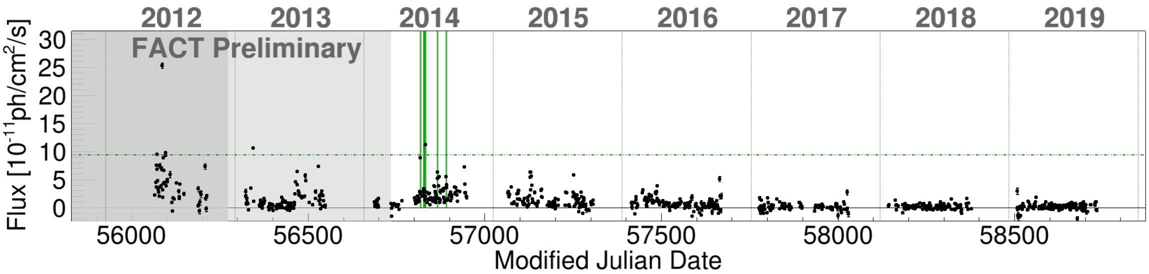
While large IACTs have a wide range of physics cases to cover, this reduces their time available for monitoring [7]. A small low-cost instrument like FACT on the other hand can focus on a small sample of bright sources to collect a continuous monitoring data sample [8]. For a sample of about five sources, nightly monitoring within the visibility window is performed with high priority. Few other sources are monitored with lower priority resulting in a less strict cadence. The scheduling is performed by an automatic algorithm [9, 10]. If possible, observations are coordinated with instruments at other wavebands. For example, simultaneous observations with Swift are realized by following the GCN (GRB Coordinates Network) notices with the pointing position of the satellite and automatic repointing for the main monitoring targets. The automatic handling of the schedule ensures not only the best performance (optimization on energy threshold) but also avoids introducing a bias e.g. by following up high flux states of sources. A comparison of the FACT monitoring program with standard monitoring at very high energies is discussed in [8, 11]. Apart from the monitoring program, target-of-opportunity observations are carried out in the multi-wavelength (MWL) and multi-messenger (MM) context.

2. Results from Eight Years of TeV Monitoring

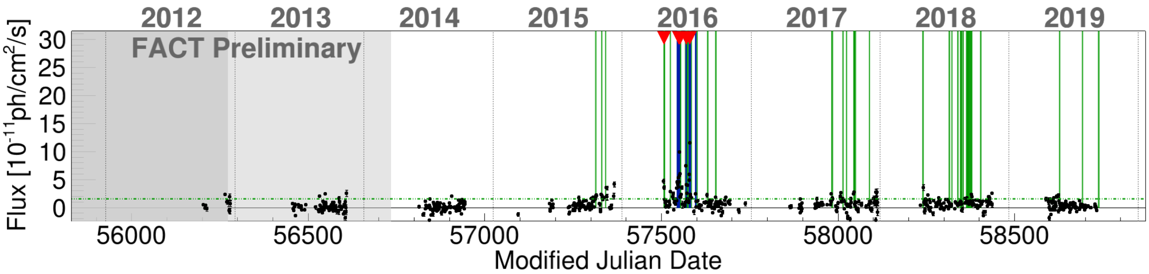
The following sections will give an overview on results from eight years unbiased monitoring. The whole data sample comprises about 14 900 hours of physics data. During one year, up to 2 400 hours have been collected [6] thanks to the high data taking efficiency and the ability to observe during bright light conditions.



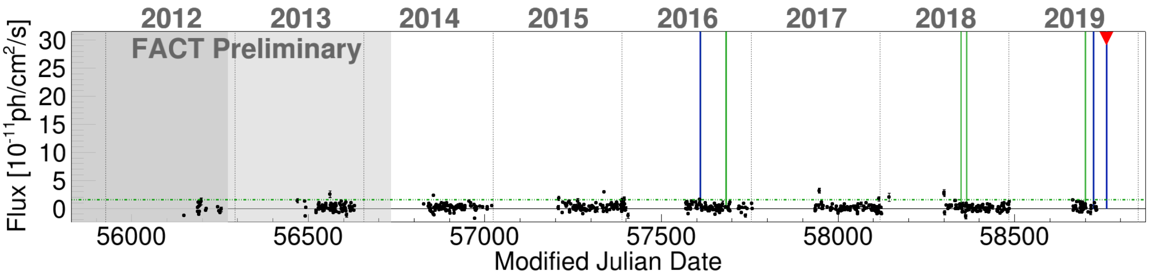
(a) Mrk 421



(b) Mrk 501



(c) 1ES 1959+650



(d) 1ES 2344+51.4

Figure 1: Long-term light curves in nightly binning over eight years as measured by FACT for (from top to bottom): Mrk 421, Mrk 501, 1ES 1959+650 and 1ES 2344+51.4. The shaded areas represent the time ranges without automatic low-latency quick-look analysis (dark gray) and without official alerts (light gray). Since March 2014, alerts are sent to the community. Different alerts are indicated with vertical lines in different colours. In green, the alerts to the gamma-ray community and MWL collaborators are marked. The trigger limits for those are marked with horizontal dashed green lines. Alerts and triggers to X-ray satellites are marked in blue (*Swift*-XRT), violet (*INTEGRAL*) and pink (*XMM-Newton*). Astronomer's Telegrams informing the whole astronomy community are indicated with red triangles.

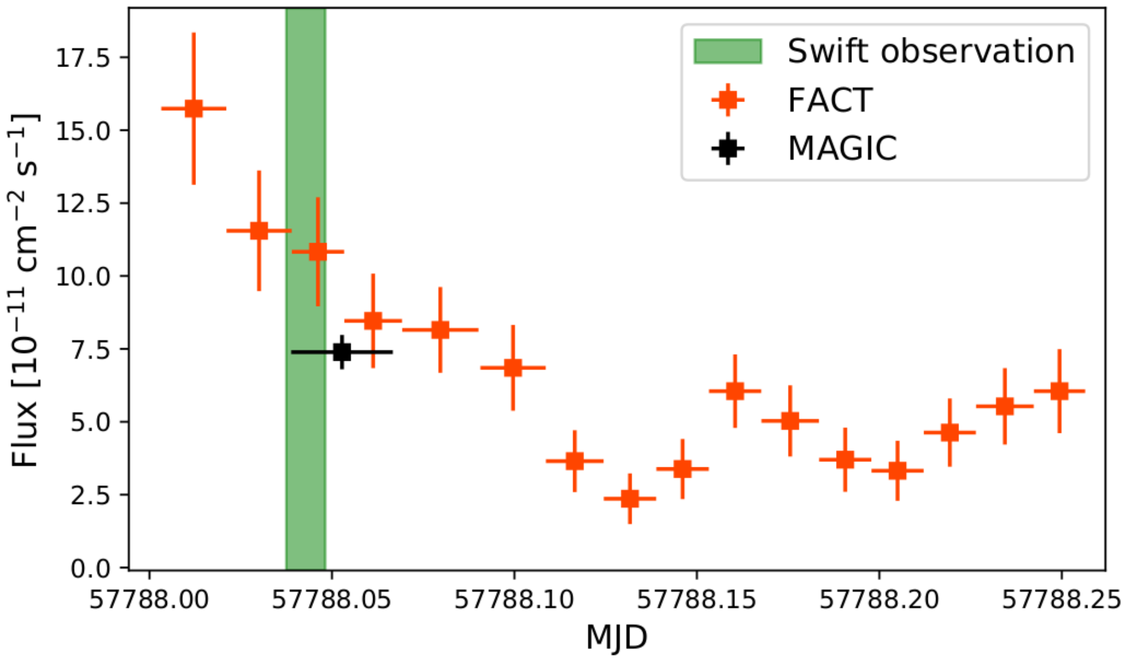


Figure 2: Very-high energy light curve of Mrk 421 during the night of Feb 1st to Feb 2nd 2017. FACT data in 20-min binning are shown in orange, MAGIC data (from [12]) in black. The observation window of *Swift* is indicated as green area.

2.1 Long-Term Light Curves and Flare Alerts

The long-term light curves from the FACT monitoring program are shown in Figure 1 in nightly binning. Alerts to MoU-partners, MWL-collaborators and X-ray satellites are indicated as vertical lines in different colour. In addition, Astronomer's Telegrams alerting the whole astronomy community about interesting events are shown as red triangles. Since March 2014, more than 100 alerts have been sent already to MoU partner and MWL collaborators, where for different objects different trigger thresholds are being used (green, dashed, horizontal lines in Fig. 1). For Mrk 421 and Mrk 501, an alert is sent, when the flux in nightly or 20-min binning exceeds the flux of the Crab Nebula at TeV energies (Crab Unit, CU) by a factor of three. For all other sources, a trigger limit of 0.5 CU in nightly or 20-min binning is used. Automatic alerts with the same limits are sent to the AMON network. In case of interesting flaring activity, target-of-opportunity (ToO) observations with *Swift* (XRT and UVOT) are triggered. Based on proposals, ToO observations of *INTEGRAL* and *XMM-Newton* are triggered [13]. The resulting broad-band spectra are studied in the MWL context [13, 14]. Based on a trigger to MoU partners and MWL collaborators, 1ES 2344+51.4 was found to be an intermittent extreme blazar [15, 16].

2.2 Multi-Wavelength Campaigns

In the context of the monitoring program, FACT also participated in a variety of MWL campaigns. During an outburst in February 2017, FACT measured intra-night variability of Mrk 421 as shown in Figure 2. The details of the MWL campaign, which includes *NuSTAR* observations, is discussed in [12, 17]. In 2015 and 2016, Mrk 421 was found in a rather low flux state [18, 19].

During this campaign, hints for an additional component in the hard X-ray regime were found. In January 2019, a joint 1-week observation campaign together with AstroSAT and WEBT has been carried out.

2.3 Long-Term Variability and Correlation Studies

Thanks to the unbiased observing strategy, the monitoring program by FACT provides an unprecedented data sample which is ideally suited for long-term studies of blazars in the MWL context. For both Mrk 421 and Mrk 501, a MWL data sample of 5.5 years has been studied in detail [20–22]. The long-term behaviour of 1ES 1959+650 is studied in detail comparing the low state in 2019 with the high state in 2016 [23].

The combination of FACT monitoring at TeV energies with *Fermi*-LAT monitoring at MeV-GeV energies provides an unbiased view on the variability in the high-energy bump of blazar SEDs. Comparing the variability characteristics of low-energy peaked blazars in Fermi and high-energy peaked blazars in FACT, no asymmetry of flares longer then one night has been found [24]. Using different methods, a search for periodic signals is carried out [25].

2.4 Follow-Up Observations

Apart from the monitoring program, ToO observations are carried out in the MWL and MM context depending on the visibility constraints and the available information. Automatic follow-ups are implemented for IceCube neutrino alerts [26] and gamma-ray bursts, both type of alerts received via GCN notices. The follow-up criteria for those are discussed in [10]. Furthermore, alerts by HAWC are followed up on a best-effort-basis. Two types of alerts are received by email under an MoU: the online flare monitor, which is based on the detection of variability using bayesian blocks [27, 28], and hotspots in the all-sky map on different time scales (0.5, 1, 2 and 3 transits) [29]. Apart from those, other alerts or interesting events communicated by email or via Astronomer's Telegram are followed up. In total, so far 50 alerts from different channels have been followed up. 27 of those since May 2019, when the automatic follow-up procedure for GRBs and neutrino alerts has been implemented [10].

3. Conclusion and Outlook

As a low-cost project and thanks to its excellent performance, FACT is ideally suited for long-term monitoring and unbiased variability studies. Operational since October 2011, more than 14 900 hours of physics data have been collected. A small sample of bright blazars is monitored with a daily cadence within in the visibility windows providing a unique data sample of up to 3200 hours per source. The unbiased data sample is better suited for systematic variability studies and correlation with other wavelengths. MWL studies for Mrk 421 and Mrk 501 on about 5.5 years of data support the SSC scenario [21, 22]. While flares longer than one night do not show any asymmetry [24] and their separation is consistent with those expected in the case of Lense–Thirring precession of the accretion disc [22], shorter flares and studies of intra-night variability (as shown in Fig. 2) need more and denser monitoring. While snapshots of broad-band spectral energy distributions can usually be explained with simple models, time-resolved spectral energy distributions are the key to discriminate between different emission models [30]. For this, ToO observations and snapshots of flares are not sufficient, but continuous monitoring is crucial.

Remark Suffering a technical problem just at the start of the pandemic end of 2019, the building and testing of the replacement piece was delayed due to the limited access to the laboratories in Europe. Also the travel to repair the telescope was delayed due to covid19. Finally in early summer 2021, the telescope resumed operation.

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