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FACT - Searching for periodicity in five-year light-curves of Active Galactic Nuclei

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The First G-APD Cherenkov Telescope (FACT) has been monitoring Active Galactic Nuclei (AGN) for the past five years. The use of robust silicon photomultipliers (SiPMs) allows for a continuous, unbiased sampling even during bright-light conditions. This dataset promises insights into the core regions of AGN by investigating the periodicity of the sources. Periodic changes in the flux could indicate a binary nature of the supermassive black holes.
A study using the Lomb-Scargle periodogram to find periodicity in monitored AGN is presented. Repeating patterns in the observation times, like moon periods and seasonal effects, affect the analysis by introducing spurious peaks into the periodogram. The zenith-dependence of the observed γ-ray rates further complicate the interpretation. Showing no variability at TeV energies, the γ-ray flux of the Crab Nebula is used to characterize this latter effect, before applying the Lomb-Scargle algorithm.

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1. Introduction

The First G-APD Cherenkov Telescope (FACT) is located on the Canary Island of La Palma. FACT is a pathfinder telescope equipped with a camera made up of silicon photomultipliers (SiPMs, consisting of Geiger-mode Avalanche Photodiodes (G-APDs)). The SiPMs are suited for observations under bright conditions, e.g. full moon, which allows FACT to have a hight duty cycle and to provide densely sampled light-curves. More information on FACT and the long-term performance of the SiPMs can be found in [1] and [2].

FACT is dedicated to long-term monitoring of the brightest Active Galactic Nuclei (AGN) in the night sky, focusing on Markarian (Mrk) 501 and Mrk 421. This dedication to monitoring in combination with the high duty cycle make FACT an ideal instrument to study the temporal evolution of AGN. AGN show highly variable fluxes on different time scales over a broad range of the electromagnetic spectrum [3]. An underlying periodicity in this variability has been claimed in γ-rays in [4], where a sinusoidal signal with a 23-day period is stated.

The following analysis aims to find periodicity in the light-curves of Mrk 501 and Mrk 421 using the Lomb-Scargle periodogram. As periodogram analysis is susceptible to artificial trends in the data, introduced by e.g. the position of the source in the night sky, the dependence of the γ-ray excess rate on the zenith angle of the source is modeled and accounted for in the data first.

2. Correcting the zenith angle Dependence

The goal of the following analysis is to quantify the zenith angle dependence of the γ-ray rate measured by FACT.

2.1 Model of Zenith Angle Dependence

In order to quantify the zenith angle dependence of the γ-ray rate, a simple model is constructed, using basic relations from the development of extensive air showers (EAS) in an isothermal atmosphere. The differential rate of γ-rays detected by the telescope is given by

$$\frac{\mathrm{d}R(E)}{\mathrm{d}E} = \Phi(E) \cdot A_\gamma^{coll}(E), \tag{2.1}$$

where $\Phi(E)$ is the differential γ-ray flux of the source and $A_\gamma^{coll}(E)$ the energy-dependent effective collection area of the telescope. The latter includes the trigger efficiency, energy threshold, light pool area of the Cherenkov radiation, etc., and is usually retrieved by Monte Carlo simulations.

The light-pool area A is the base area of the Cherenkov light cone perpendicular to the telescope axis. It is assumed to only depend on the height h_{max} of the shower maximum. However, h_{max}, measured in meters from the height of the telescope above sea level, introduces both the zenith angle- as well as the energy-dependence into the calculation of A: $h_{max} = h_{max}(E,\theta)$:

$$A(E,\theta) = \pi h_{max}^2(E,\theta) \cdot \tan^2(\theta_C). \tag{2.2}$$

θ_C is the opening angle of the Cherenkov light cone, which depends on the refractive index of the atmosphere. For an isothermal atmosphere, θ_C depends on the density only. It is assumed that height h_{max} only varies slightly between the showers, therefore the density and θ_C can be regarded as constant. It is set to $\theta_C = 1.4^\circ$. The height h_{max} is related to the atmospheric depth X_{max} of the shower maximum, measured in $\mathrm{g\,cm^{-2}}$, via the barometer formula

$$\frac{X_{max}(E,\theta)}{X_0} = \exp\Big(-\frac{h_{max}(E,\theta)}{h_0}\Big), \tag{2.3}$$

where h_0 is the scale height of the atmosphere and X_0 the atmospheric slant depth at vertical incidence of the shower (vertical column density of atmosphere). The scale height is constant, except for a geometrical dependence on the zenith angle θ:

$$h_0 = h_0(\theta) = \frac{kT}{mg} \cdot \frac{1}{\cos\theta}. \tag{2.4}$$

X_0 is used to set the height of primary interaction in terms of the atmospheric column density, it is set to $1035\,\mathrm{g\,cm^{-2}}$, its energy dependence is neglected.
The atmospheric depth X_{max} of the shower maximum introduces the dependence of the primary particle's energy into the model. Following the energy splitting approximation for electromagnetic cascades as derived in [5], is is given by

$$X_{max} = \frac{\ln(E_0/E_C)}{\ln 2} \cdot R_e. \tag{2.5}$$

Here, E_0 is the energy of the primary particle, E_C is the critical electron energy where energy losses due ionization and bremsstrahlung are equal, and R_e is the radiation length of electrons in air. $E_C \approx 86\,\mathrm{MeV}$ and $R_e \approx 28.9\,\mathrm{g/cm^2}$. As hadronic showers are dominated by their electromagnetic components, it is assumed that Eq. 2.5 is valid in first approximation for cosmic ray showers.
The dependence of the slant depth $X(\theta)$ on the zenith angle is given a free parameter in this model. While the first order geometrical dependence is accounted for with a $1/\cos\theta$ term, $X(\theta)$ also contains higher order corrections (e.g. due to the curvature of the earth). It was found that adding another free fit parameter a

$$X(\theta) = \frac{X_0}{cos^a\theta} \tag{2.6}$$

results in a good description of the data.
The scaling of the slant depth is therefore a function of the zenith angle. The energy threshold of the telescope is known to be zenith angle dependent: The farther the shower maximum is away from the telescope, the lower the photon density is on the ground: $E_{thresh} \propto 1/\cos^2\theta$. The dependence of the energy threshold is combined with the dependence of the slant depth $X(\theta)$ on the zenith angle, in the form of

$$E_{thresh} \propto \left(\frac{X(\theta)}{X_0}\right)^b \cdot \exp\Big(c \cdot \frac{X(\theta)}{X_0}\Big), \tag{2.7}$$

following [6]. A free parameter b is introduced as it allows for a better fit of the data. The second, exponential term in the equation is introduced to account for an increase of the energy threshold due to increased attenuation of the Cherenkov light by the atmosphere. b and c are the second and third free fit parameters of the model. The final fit function is then given by

$$R(\theta) = \int_{E_{thresh}(\theta)}^{\infty} \Phi(E) \cdot A(E,\theta)\mathrm{d}E = \int_{E_{thresh}(\theta)}^{\infty} \Phi(E) \cdot \pi h_{max}^2(E,\theta) \cdot \tan^2(\theta_C)\mathrm{d}E. \tag{2.8}$$

Eq. 2.8 allows for a good fit of the measured rates for both CR and excess γ-rays with the free parameters a, b, and c.

2.2 Application to Cosmic-Ray Rates

To verify the applicability of the above derived model function, the dependence of the rate of cosmic rays (CR) measured by FACT on the zenith angle is fitted. The rates are calculated by the analysis chain at the ISDC in Geneva. Using the fit results, data taken during bad atmospheric conditions are identified. The basic idea is described in [7].

Fig. 1 shows the rate of CR as function of the zenith angle. A virtual trigger threshold was used to calculate the CR rate. The trigger threshold was set slightly higher than in [7] to ensure that the zenith-dependence is the dominating factor for the decrease of the rate.
The rate drops off for larger zenith angles. The effect of bad weather during observations is visible, decreasing the rates within the zenith angle bins. For this sample, only observation runs with durations of at least 4 minutes were considered. The higher density of rates around 6°, 10° , 23°, and 35° zenith angle are caused by sources culminating at these zenith angles. FACT aims to observe sources at culmination.

The data is binned by zenith angle, and the distribution of rates for each zenith bin is plotted. The maximum of the gaussian kernel density estimator (KDE, [8]) is used to define the average value, ensuring that it is only minimally affected by bad weather observations. The uncertainty on this rate is given by the FWHM of the KDE peak.

Using the average rates obtained for the zenith angle bins, the model function is fit to the CR rates. The fit function is shown in orange in Fig. 1, the fit parameters are a=1.5, b=0.93, c=0.78.

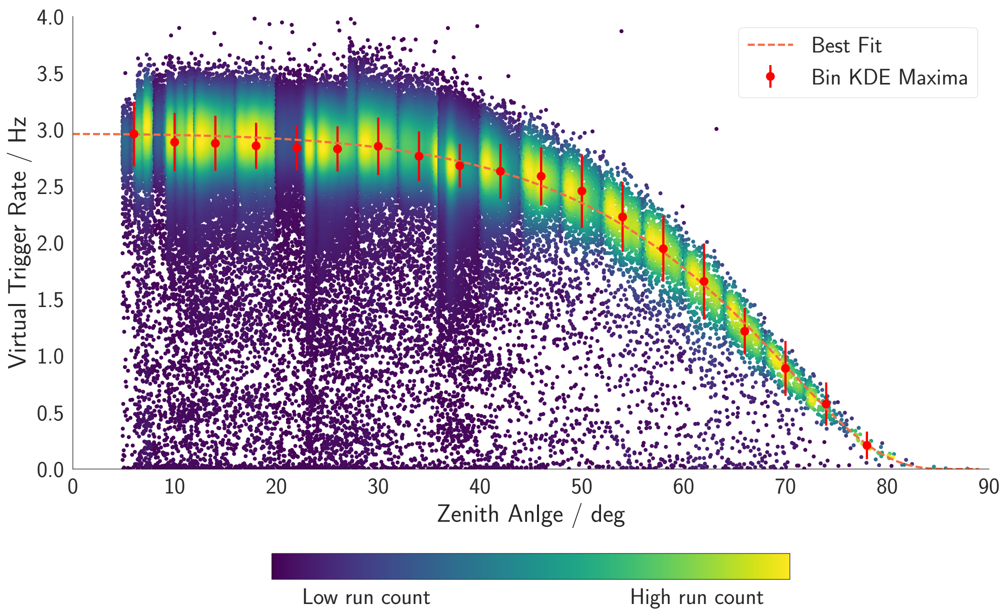

Figure 1: Fit of model function to the CR rate over zenith angle: The rate of cosmic rays using an artificial trigger over the zenith angle of the pointing direction of the FACT telescope. The cosmic ray rate coming from the direction of the seven most observed sources by FACT. A clear drop-off of the rate towards large zenith angles is visible. The position of the KDE maxima for each bin is superimposed in red. Shown as orange, dashed line is the fit of the model function.

The obtained fit function given in Eq. 2.8 is now used to correct for the zenith-dependence of the run rates, by normalizing to the model value at $\theta = 0°$. Bad weather runs are then identified by calculating the KDE of the corrected run distributions. The peak in the distribution around 3 Hz is then fit using a Gaussian distribution. The lower rate at which the Gaussian fit distribution is more than 10 % smaller than the KDE is chosen as upper limit for bad weather runs.

2.3 Correcting the Crab Nebula γ-ray Rates

The bad-weather runs identified above, as well as observation runs with times shorter than 4 minutes are excluded from the data. 18.4 % of all observation runs are filtered due to bad weather. In Fig. 2, the rate of excess rates calculated in zenith angle bins is shown as blue data points. The model function was fitted to the bin rates, shown in red. The fit parameters here are: a=1.22, b=0.98, c=1.23. These differ from the parameters for the artificial trigger rates. This is probably due to the difference in hadronic and electromagnetic showers, which was not regarded in the model.

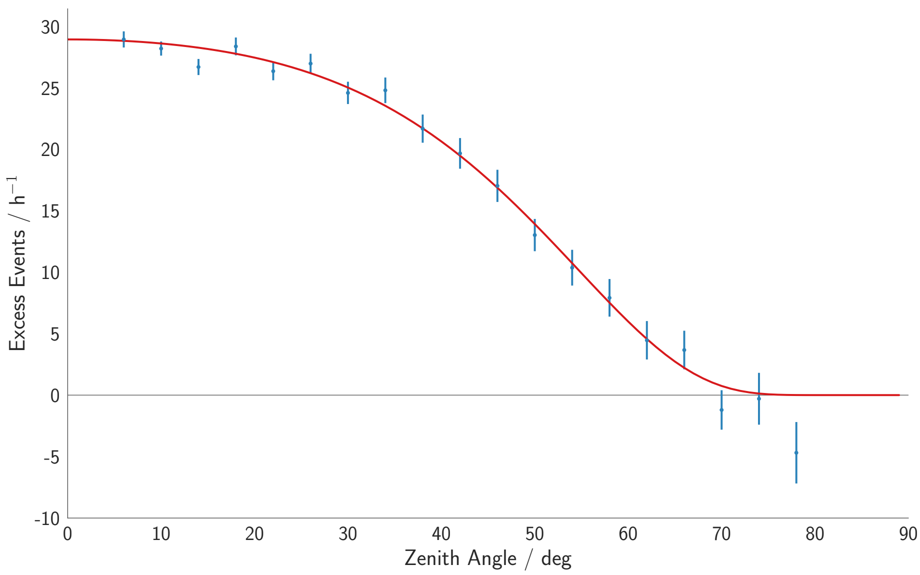

Figure 2: Fitted Crab γ-ray excess event rates: The Crab excess event rates binned by zenith angle are shown in blue, with the fitted model function shown in red. For the parameters, see text.

3. The Lomb-Scargle Analysis

The Lomb-Scargle (LS) periodogram (or Least-Squares Spectral Analysis) is a brute-force approach to identifying sinusoidal signals in time-series data with least-squares fitting. A sinusoid is fitted to the data over a grid of frequencies, and the resulting minimization parameter χ^2 is compared to that of the null hypothesis; a constant signal with purely Gaussian noise. The resulting periodogram shows peaks at frequencies that best fit the data. For more information on the Lomb-Scargle periodogram and its application, the reader is referred to [9] and [10].
To show the effect of the correction derived in Chapter 2, the LS periodogram of the light-curve of the Crab Nebula acquired by FACT before and after the zenith-correction is computed. The Crab

Nebula is a supernova remnant frequently used for calibration purposes in Cherenkov astronomy. A constant rate of γ-rays over time is expected, equivalent to a featureless LS periodogram. Peaks in the periodogram of the Crab Nebula can therefore be used to find systematic trends in the data. The correction is applied to the single observation runs, assuming that the zenith angle of the Crab Nebula is remaining constant over the run duration of five minutes. The observation runs of a single night are then grouped together to yield nightly rates. Fig. 3 shows the LS periodogram of the Crab Nebula light-curve before (red, dashed lines) and after (blue, solid lines) the zenith angle correction is applied. On top is the rate of excess γ-ray events as measured by FACT. The applied correction is strongest around September and April, when the Crab Nebula is at larger zenith angles.
The bottom row in Fig. 3 shows the LS periodogram of the data. Visible is a forest of peaks towards smaller periods both with and without the correction applied, introduced by the noise of the light-curve. The broad, dominant peak at 373 days is inherent in the light-curve before the correction, and caused by the decreasing rates when the Crab Nebula is at increasingly larger mean zenith angles during the night. The peak at 122 days is correlated with the peak at 373 days, it is artificial and not in the data. After applying the zenith-correction, this peak has vanished, as has the alias peak at 122 days. This demonstrates that the zenith angle correction has the desired effect of simplifying the LS periodogram and reducing the amount of alias peaks.

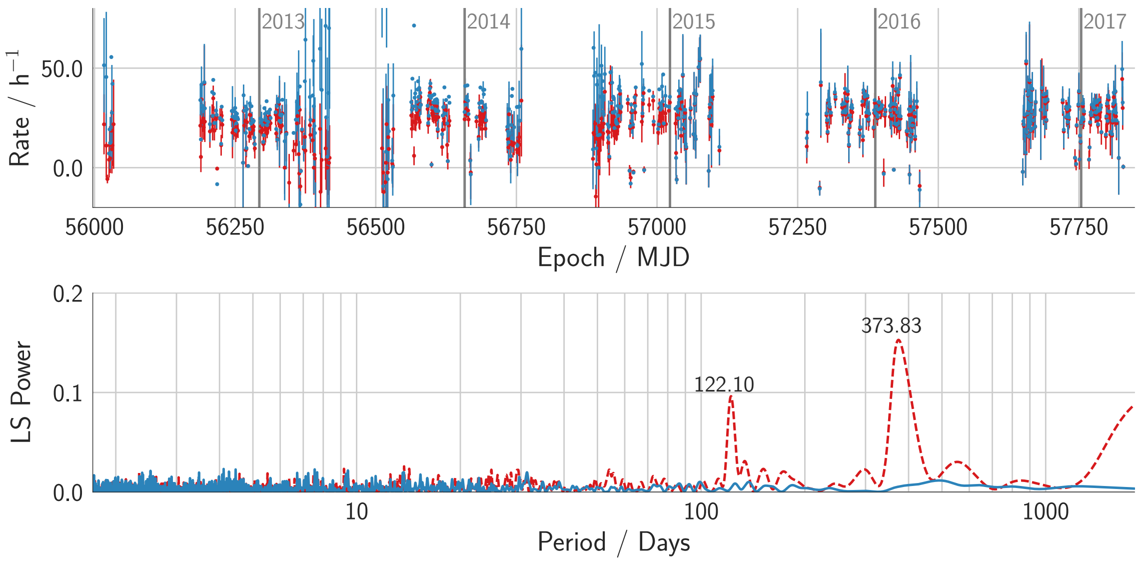

Figure 3: Lomb-Scargle analysis of the Crab Nebula before and after zenith angle correction: (Top) The nightly excess event rates measured (red) and corrected (blue). (Bottom) The LS periodogram of the measured light-curve (red) and the corrected one (blue)

Fig. 4 and Fig. 5 show preliminary results of the application of the LS algorithm of the zenith angle corrected light-curves of Mrk 501 and Mrk 421 respectively. The peaks in the periodogram cannot yet be used for a conclusion on the periodicity of theses sources, as the data check is ongoing and artificial peaks can still dominate the periodogram. Some periods in the data continue to be affected by changes in the telescope system (e.g. misaligned mirrors). This systematic changes in the rate are still being considered and accounted for.

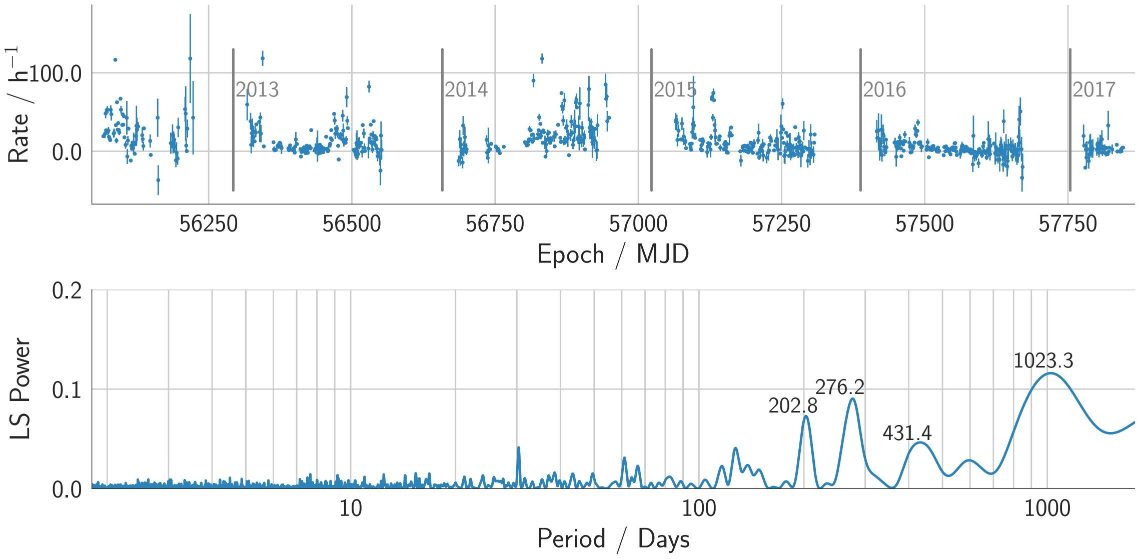

Figure 4: Lomb-Scargle analysis of zenith angle corrected light-curve of Markarian 501: (Top) The light-curve acquired by the FACT telescope. (Bottom) The Lomb-Scargle periodogram of the light-curve.

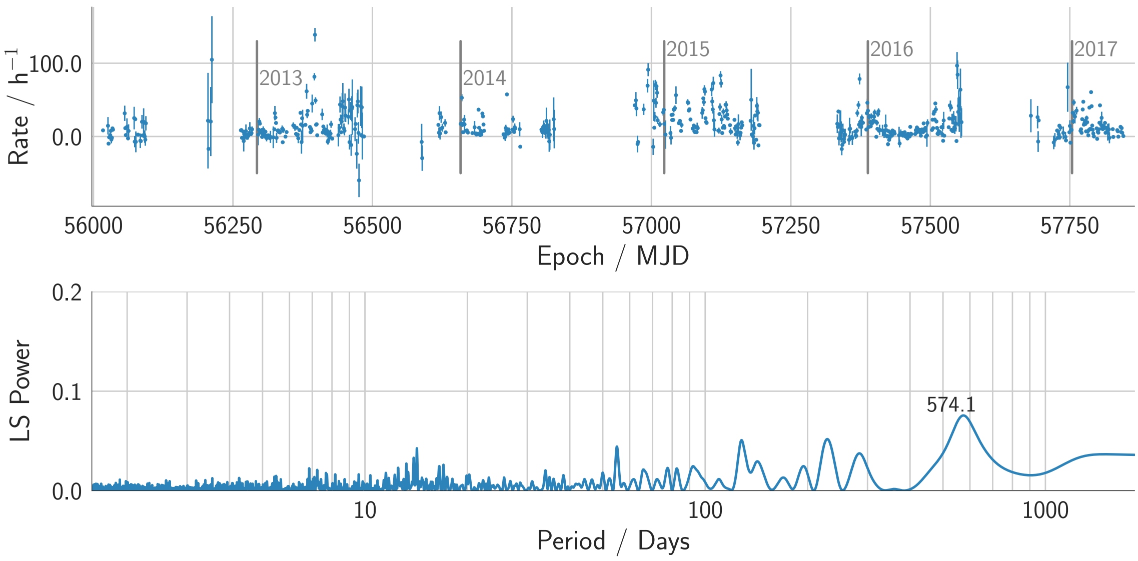

Figure 5: Lomb-Scargle analysis of zenith angle corrected light-curve of Markarian 421: (Top) The light-curve acquired by the FACT telescope. (Bottom) The Lomb-Scargle periodogram of the light-curve.

4. Conclusion and Outlook

The FACT telescope is well-suited for time-series analysis of AGN as it provides densely sampled light-curves. A qualitative model was derived to correct for the zenith angle dependence of the excess γ-ray flux. The model was used on the rate of cosmic rays to find data taken during bad atmospheric conditions and to correct for the decrease of the rate towards large zenith angles in the light-curves of the Crab Nebula, Mrk 501, and Mrk 421. The successful application of this correction was demonstrated using the LS periodogram of the Crab Nebula data. Next steps include improving the data check by correcting changes in the rate due to changes in the telescope system, as well as a study on the significance of the peaks in the LS periodograms of Mrk 501 and Mrk 421.

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