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ESTIMATION OF THE FLARE DUTY CYCLE OF AGNS BASED ON LOG-NORMAL RED-NOISE PROCESSES

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Abstract. Active Galactic Nuclei (AGN) show variability on time scales ranging from years down to minutes, e.g. in the TeV band, with outbursts often called flares. We aim at estimating the number of flares observable during a long-term monitoring campaign, depending on their flux and variability time scales. We use backward Fourier transform to construct AGN light curves as realizations of a pseudo-red-noise, log-normal process. Using a simple definition of a flare, we map their duty cycle as a function of threshold-flux and flare-duration values. The flare duty cycle can be entirely defined by two quantities: the slope of the power spectral density and the normalized variance of the process. We also produce visibility windows in order to estimate the effect of sampling on the observable number of flares.

Keywords: galaxy: nucleus, galaxies: active, gamma rays: galaxies, methods: statistical

1 Introduction

An active galactic nucleus (AGN) is a compact region in the center of a galaxy, which consists of a supermassive black hole with an accretion disk. AGNs emit relativistic jets and have strong radiation with flux variability from radio to γ-ray. However, the definition of an AGN flare, providing the amplitude and duration of flux variations, can be ambiguous. What fraction of the time does an AGN spend above a given flux with a coherent behavior? We propose a simple definition that can be used to jointly study the flux distribution and variability time scales of flares. We evaluate the duty cycle of AGN flares through simulations, assuming that the emission can be modeled as a red-noise, log-normal process.

2 Method

Long-term high-energy observations from *Fermi*-LAT reveal AGN light curves behaving as red-noise processes (Abdo et al. 2010). This means that the power spectral density (PSD) of the observed lightcurves follows a power-law spectrum as a function of frequency, $P(f) \sim f^{-\beta}$, where β is the index of the PSD and $P(f)$ is the power at frequency f. The average power-law index of FSRQs and BL Lacs was estimated by Abdo et al. (2010) to be $\beta = 1.4 \pm 0.1$ and $\beta = 1.7 \pm 0.3$, respectively.

The variations in flux are furthermore often found to have a log-normal distribution and the average amplitude of variability is proportional to the flux level (e.g. Giebels & Degrange 2009). The amplitude of flux variations is sometimes characterized by the fractional root mean square (rms) variability, $F_{\rm var}$, which is an estimator of the rms flux divided by the average flux. TeV γ-ray observations of PKS 2155−304 by the High Energy Stereoscopic System (H.E.S.S.) for example displayed strong flux variability with fractional rms variations between $F_{\rm var} = 0.13 \pm 0.09$ and $F_{\rm var} = 0.67 \pm 0.03$ (Abramowski et al. 2010).
In the following, we simulate light curves from log-normal flux distributions based on red-noise processes, investigating $F_{\rm var} = 0.1,\ 0.5$ and $\beta = 1,\ 2$ as test values. Timmer & Koenig (1995) propose a method for generating AGN light curves from a red-noise process. Here are the steps of our simulations:
(1) We construct a random PSD following a power-law spectrum of index β. We draw two normally distributed random numbers for each Fourier frequency f_i and multiply them by $\sqrt{P(f_i)/2} \sim f_i^{-\beta/2}$. The results are used as the real part and imaginary part of the Fourier transform. Light curves are then generated through backward

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Fourier transform. We notice that such simulations can be affected by windowing and aliasing effects (Uttley, McHardy & Papadakis 2002), but we do not consider these two effects at the early stage of this study.
(2) To get a log-normal distribution, we exponentiate the flux values, $\Phi_{TK}(t)$, from the light curve obtained with the method of Timmer & Koenig (1995), noting that small distortions of the PSD are expected. $\Phi_{TK}(t)$ represents here a red-noise Gaussian process with an average of 0 and variance of 1. We rescale $\Phi_{TK}(t)$ so that the average of Φ_t is set to 1 arbitary units and its fractional rms amplitude is set to a value of $F_{\rm var}$. We obtain the corresponding log-normally distributed random flux Φ_t, using two parameters μ and σ that are the mean and standard deviation of the natural logarithm of Φ_t:

$$\Phi_t = \exp(\mu + \sigma\Phi_{TK}(t)). \tag{2.1}$$

We set $\mu = -\frac{1}{2}\ln(1 + F_{\rm var}^2)$ and $\sigma^2 = \ln(1 + F_{\rm var}^2)$, which indeed results in $< \Phi_t >= 1$ and $\sigma_{\Phi_t}/ < \Phi_t >= F_{\rm var}$. In the method described above, only two parameters, β and $F_{\rm var}$, are needed to fix the statistical characteristics of the light curves and therefore to describe the flare duty cycle.
For each lightcurve, we define flares above a given flux threshold as events for which the emission remains strictly above the threshold for a given duration. We collect the start and stop times of each flare for various realizations of the lightcurves and store the duration of each flare in a 2D histogram. We define the flare duty cycle as the ratio between the sum of flare durations and the light curve duration.

3 Results

Fig. 1, left, shows a single AGN light curve simulated as a pseudo-red-noise, log-normal process. We set $\beta = 2$ and $F_{\rm var} = 0.5$ as an example that is in rough agreement with γ-ray observations from *Fermi*-LAT and H.E.S.S. We assume here an observation duration of 1 week, and a sampling of the flux every 0.5 hour.

Fig. 1, right, shows the flare duty cycle as a function of the flare duration and threshold flux obtained from simulations of 10^4 lightcurves, with the same β and $F_{\rm var}$ values as set to generate Fig. 1, left. We checked that integrating the 2D histogram over flare durations for given flux thresholds results in a 1D distribution compatible with the cumulative distribution function expected from a log-normal process.

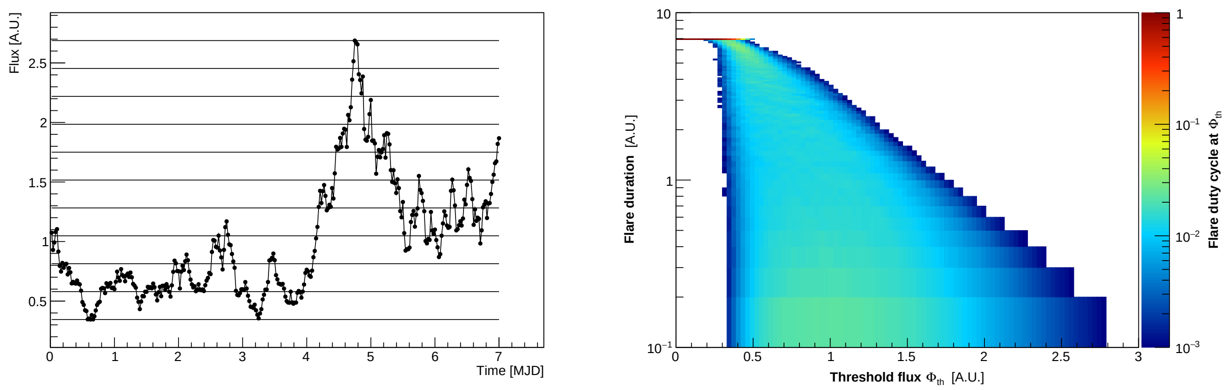

Fig. 1. Left: Example of a simulated light curve obtained with $F_{\rm var} = 0.5$ and $\beta = 2$. Horizontal lines illustrate threshold fluxes above which the start and stop times of flaring events are collected. **Right:** Flare duty cycle obtained with $F_{\rm var} = 0.5$ and $\beta = 2$.

3.1 *Varying* β *and* $F_{\rm var}$

The distribution of flare duty cycle depends on β and $F_{\rm var}$. The index of the PSD, β, reflects the ratio of long-term fluctuation power and short-term fluctuation power while the fractional rms variability, $F_{\rm var}$, reflects the average amplitude of the variations.

In Fig. 2, left, we illustrate the duty cycle obtained with $\beta = 1$ and $F_{\rm var} = 0.5$ for 10^4 simulations. In Fig. 2, right, we choose to illustrate the behavior of the duty cycle for $F_{\rm var} = 0.1$ and $\beta = 2$.
(1) The comparison of Fig. 2, left, ($\beta = 1$) and Fig. 1, right, ($\beta = 2$), shows that for larger β values, the flare duty cycle covers a wider area of the flare duration − threshold flux plane. The interpretation is that, as β is

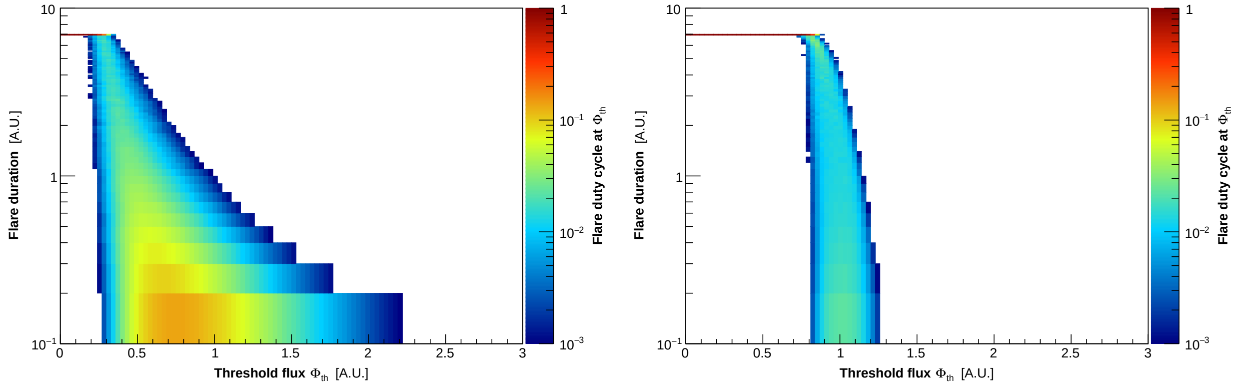

Fig. 2. Left: Flare duty cycle obtained with $F_{\rm var} = 0.5$ and $\beta = 1$. **Right:** Flare duty cycle obtained with $F_{\rm var} = 0.1$ and $\beta = 2$.

larger, more variability power is present at low frequencies. Long-duration flares are more frequent, and more time is given to build up large amplitude variations.
(2) The comparison of Fig. 2, right, ($F_{\rm var} = 0.1$) and Fig. 1, right, ($F_{\rm var} = 0.5$) also shows that for higher $F_{\rm var}$, the flare duty cycle covers a wider area of the flare duration – threshold flux plane. The interpretation is that, as $F_{\rm var}$ is larger, the flux can vary in a larger range and spread out more. Larger amplitude flares build up, but the time scale distribution remains similar to that observed in Fig. 1, right.

3.2 Simulations with observation windows

Ground-based γ-ray observations from imaging atmospheric Cherenkov telescopes such as H.E.S.S., MAGIC, and VERITAS, are usually performed during dark, moonless nights, so that realistic light curves are affected by observation windows. We illustrate in Fig. 3 the effect of windowing on a single realization of a light curve from the method discussed in Sec. 2. The red points correspond to a 5-week-long lightcurve sampled on a 0.5-hour timescale, while the black points correspond to the subsample of observations falling within H.E.S.S. visibility, assuming a source located in the direction of PKS 2155–304. We follow the visibility definition of Giomi, Gerard & Maier (2016) and exploit the code from these authors, which is based on AstroPy (`http://www.astropy.org/`). In the example chosen here, PKS 2155–304 can only be observed by H.E.S.S. in blocks of 4-5 consecutive days.

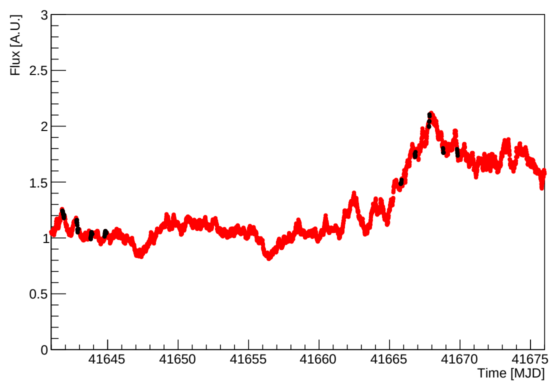

Fig. 3. Simulated light curve with $F_{\rm var} = 2$ and $\beta = 0.5$ over a 5-week term (red points) with a 0.5-hour sampling. Black points illustrate the visibility of a given source by a ground-based γ-ray observatory.

Fig. 4, left, shows the flare duty cycle obtained by simulating 10^4 lightcurves with characteristics similar to the red curve in Fig. 3 (no windowing). Fig. 4, right, shows the flare duty cycle obtained by simulating the

same lightcurves affected by windowing, i.e. lightcurves similar to the black points in Fig. 3.
The mapping of the flare duty cycle is clearly affected by the observational windowing, with characteristic time scales imprinted directly in the 2D histogram. Further studies will be dedicated to understanding how the duty cycle is distorted by the observation schedule and to how one could optimize long-term monitoring campaigns to minimize biases inherent to the windowing, e.g. in the context of long-term observations with the Cherenkov Telescope Array.

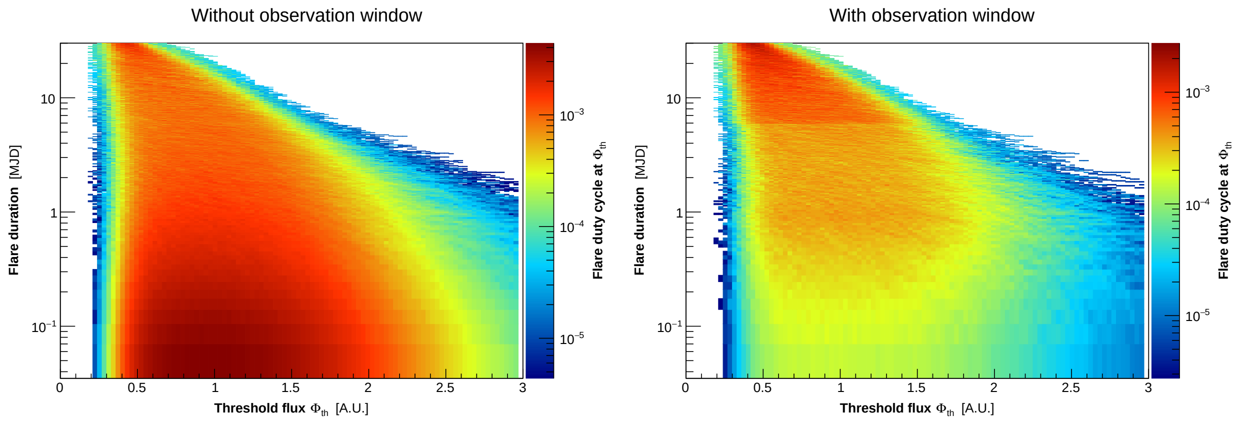

Fig. 4. Left: Flare duty cycle obtained with $F_{\rm var} = 0.5$ and $\beta = 2$ for a 5-week-long lightcurve. No observation window is considered. **Right:** Flare duty cycle obtained with the same simulations applying the observation windows illustrated in Fig. 3.

4 Conclusions and outlook

We have adopted a simple definition of flaring events from AGNs to jointly investigate the flux distribution and variability timescales of pseudo-red-noise, log-normal processes. We summarized the main conclusions here:
(1) We can estimate the duty cycle for any fractional rms variability, $F_{\rm var}$, and power spectral density index, β, as a function of the flare duration and threshold flux. All the flare information can be derived from these two parameters.
(2) Larger $F_{\rm var}$ values correspond to a wider range of flux variations, affecting the mapping of the flare duty cycle as a function of the threshold flux. Larger β values correspond to more power at low frequencies, resulting in longer flares as well as higher-amplitude flares, which have sufficient time to build up.
(3) The observational windowing affects the mapping of the duty cycle. Long-term monitoring campaigns could exploit tools such as presented in these proceedings to optimize the mapping of the duty cycle of AGN flares.
In the future, further developments for long-term γ-ray monitoring campaigns could include:
(1) A joint, unbiased, determination of $F_{\rm var}$ and β based on observations (e.g. from *Fermi*-LAT), focused on archetypal objects or populations.
(2) Simulations of long-term lightcurves to study more indepth the mapping of the duty cycle. Parallel computing appears to be a good solution to pursue such efforts.

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