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Stochastic approach to modeling the γ-ray variability of Fermi/LAT blazars

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Abstract. We studied the γ-ray variability of 13 blazars observed with the Fermi Large Area Telescope (LAT). These blazars were among the brightest ones monitored during the first 4 years of the Fermi sky survey. We modelled their γ-ray light curves with the Ornstein-Uhlenbeck (OU) process or mixed OU process. The power spectral density (PSD) of the OU process is a zero-centered Lorentzian function, proportional to $1/f^{\alpha}$ with α changing at a characteristic time scale, τ_0, from 0 ($\tau \gg \tau_0$) to 2 ($\tau \ll \tau_0$). The PSD of the mixed OU process has in addition an intermediate part with $0 < \alpha < 2$ between the long and short characteristic time scales. We show that the OU model provides a good description of the Fermi/LAT light curves of three blazars in our sample. For the first time we provide constraints on the characteristic γ-ray time scale of variability in two BL Lac sources, 3C 66A and PKS 2155-304. We find that the mixed OU process describes the light curves of the remaining 10 blazars better than the OU process. We infer that their Fermi/LAT PSD resemble power-law functions and constrain their PSD slopes.

Keywords. black hole physics, BL Lacertae objects: general, galaxies: active, galaxies: jets, gamma rays: galaxies

1. Introduction

Blazars are active galactic nuclei (AGN) producing powerful relativistic jets being prominent sources of non-thermal radiation, with one of the jets aligned closely with our line of sight. The unique blazar orientation results in relativistic boosting of this non-thermal radiation component. The γ-ray emission of blazars exhibits strong variability, suggestive of the complex nature of the underlying dissipation and particle acceleration processes. Before the launch of Fermi, thorough blazar variability studies were impaired mainly due to the lack of γ-ray blazar monitoring data, and robust statistical methods to model the variable blazar emission.

The Fermi/LAT instrument has been performing continuous observations of the γ-ray sky since 2008, which provided good quality light curves of a sample of bright blazars, and boosted the blazar γ-ray variability studies. The highest flux states of blazars are commonly described as flares, defined using the concept of the flux doubling and halving time scales (e.g. Nalewajko 2013). Such an approach suggests that flares have an origin that is distinct from that of the bulk of the γ-ray blazar variability. On the other hand, it has been demonstrated that the γ-ray power spectral densities (PSD) of blazars appear to be in the form of a power-law function (e.g. Abdo *et al.* 2010; Nakagawa & Mori 2013), pointing toward a stochastic nature of the high energy blazar variability.

Table 1. Properties of the Fermi/LAT γ-ray blazar light curves.

Name	z	$\log \tau_0$	DIC	α	$\log \tau_S$		$\log \Delta t$	$\log \tau_L$		DIC
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
FSRQs										
B2 1633+38	1.814	$-0.13^{+0.12}_{-0.12}$	1871	$1.00^{+0.06}_{-0.06}$		< -1.53	-1.3		> 2.27	1663
PKS 1424-41	1.522	$0.75^{+0.14}_{-0.12}$	1315	$0.78^{+0.10}_{-0.09}$		< -0.87	-1.4		> 2.06	1222
B2 1520+31	1.487	$-0.01^{+0.08}_{-0.08}$	2458	$1.05^{+0.08}_{-0.07}$		< -1.35	-1.3		> 2.00	2301
PKS 0454-234	1.003	$0.25^{+0.11}_{-0.11}$	1733	$0.93^{+0.08}_{-0.07}$		< -1.26	-1.3		> 2.44	1578
3C 454.3	0.859	> 2.00	254	< 0.43	$0.32^{+1.47}_{-1.22}$	< 3.21	-0.6		> 2.53	250
3C 279	0.536	$-0.01^{+0.09}_{-0.09}$	2425	$1.03^{+0.06}_{-0.06}$		< -1.53	-1.3		> 2.39	2169
PKS 1510-089	0.360	$1.03^{+0.11}_{-0.10}$	1386	$0.48^{+0.19}_{-0.20}$		< -0.16	-0.6	$2.17^{+1.52}_{-0.45}$	> 1.64	1350
3C 273	0.158	$0.38^{+0.10}_{-0.10}$	1509	$0.84^{+0.11}_{-0.09}$		< -1.03	-1.6		> 2.06	1408
BL Lacs										
3C 66A	0.444	$1.39^{+0.43}_{-0.29}$	448	$0.81^{+0.50}_{-0.44}$	$-0.03^{+0.76}_{-1.19}$	< 1.03	-0.7		> 1.87	445
PKS 0716+714	0.300	$0.17^{+0.10}_{-0.10}$	1941	$1.05^{+0.20}_{-0.16}$	$-1.10^{+0.44}_{-0.73}$	< -0.53	-1.3		> 1.82	1876
PKS 2155-304	0.116	$1.63^{+2.79}_{-0.35}$	477	$0.64^{+0.79}_{-0.50}$		< 1.61	-0.7		> 1.70	468
BL Lac	0.069	$0.47^{+0.15}_{-0.15}$	865	$0.93^{+0.18}_{-0.14}$	$-1.16^{+0.52}_{-0.72}$	< -0.46	-1.3		> 2.11	811
Mkn 421	0.030	$0.82^{+0.15}_{-0.13}$	1351	$0.94^{+0.13}_{-0.13}$		< -0.51	-0.8		> 1.78	1306

Notes: All characteristic time scales are reported in days and in the observer's frame. (1) Characteristic time scale of the OU process, τ_0, in days. (2/9) Deviance Information Criterion, DIC, for the OU/sup-OU model; models with lower DIC are preferred. (3) Slope of the PSD $\propto 1/f^{\alpha}$ between the short and long characteristic time scales in the sup-OU model (90% confidence region). (4) Short characteristic time scale in the sup-OU model, τ_S, in days (90% confidence region). (5) Upper limits on the short characteristic time scale in the sup-OU model (99% confidence region). (6) The smallest time spacing in the light curve, Δt, in days. (7) Long characteristic time scale in the sup-OU model, τ_L, in days (90% confidence region). (8) Lower limit on the long characteristic time scale in the sup-OU model (99% confidence region).

The variability methods relying on the PSD extraction require that the light curves are uniformly sampled in order to avoid observational biases, which are not trivial to account for. Models of variability applied directly to the light curves avoid these biases. We apply the stochastic models of Kelly *et al.* (2009, 2011) to the first 4-year Fermi/LAT light curves of 13 bright blazars. We present a systematic analysis of the γ-ray blazar light curves in the time domain using the parametric variability methods.

2. Method

Kelly *et al.* (2009, 2011) developed and advocated for stochastic models for luminosity fluctuations of accreting black holes. They derived the likelihood function for their statistical models and performed statistical inference within a Bayesian framework. This allowed them to obtain the probability distributions of the model parameters, such as the characteristic time scales and the PSD slopes, given the data. They fully accounted for the measuring errors, irregular sampling, red noise leak, and aliasing. In addition, direct modeling of the light curves allowed them to combine easily different sampling time scales. All these advantages make the Kelly *et al.* models particularly attractive for constraining the PSD of AGN in all energy bands. We assume that the γ-ray variability of Fermi/LAT blazars is stochastic and we model it using the methods of Kelly *et al.* (2009, 2011).

Kelly *et al.* (2009) introduced the Ornstein-Uhlenbeck (OU) process† whose PSD is a Lorentzian function centered at zero. It decreases as f^{-2} for time scales $\tau \ll \tau_0$ and is

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† The OU process is referred to in the literature also as the continuous-time first order autoregressive process, CAR(1), or damped random walk (DRW) process.

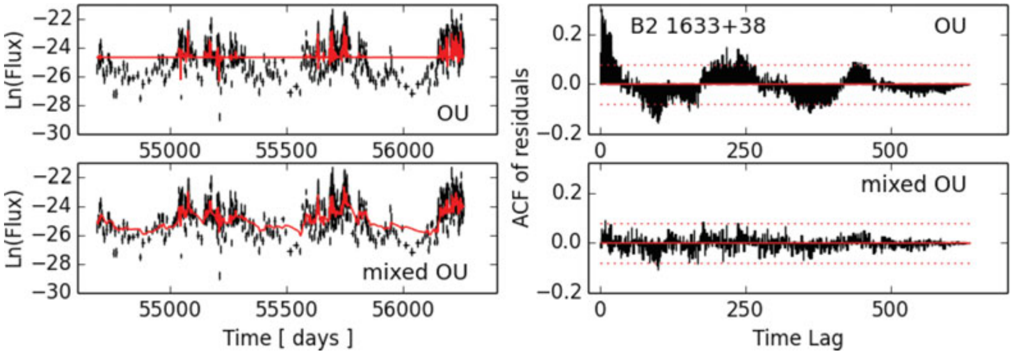

Figure 1. Left:. Maximum likelihood OU and mixed OU model realizations compared to the B2 1633+38 data (flux in ph cm^{-2} s^{-1}). **Right:**. ACFs of model residuals and 95% confidence limits assuming a white noise process (dotted lines).

constant at time scales $\tau \gg \tau_0$. Thus, τ_0 can be associated with a characteristic time scale of the process. Kelly *et al.* (2011) developed a model being a mixture of the OU processes, with PSD featuring an intermediate $f^{-\alpha}$ part ($0 < \alpha < 2$) between $\tau_{\rm long}$ and $\tau_{\rm short}$ corresponding to the low- and high-frequency PSD bends. Power-law PSDs with one or two bends have been commonly observed in X-rays in the black hole binaries (e.g. Pottschmidt *et al.* 2003, Axelsson *et al.* 2005, Belloni et al. 2005, Reig *et al.* 2013), and in optical and X-ray bands in AGN (e.g. Markowitz *et al.* 2003, Kelly *et al.* 2009).

3. Sample and data reduction

Our sample includes 13 γ-ray bright blazars: 8 flat spectrum radio quasars (FSRQs) and 5 BL Lac type sources (Tab. 1). These sources were among the brightest ones in the 2FGL catalog (Nolan *et al.* 2012) and remained bright during the 3rd and 4th year of the Fermi/LAT survey. In order to sample as wide range of variability time scales as possible, we computed adaptively binned 100 MeV–300 GeV light curves requiring that TS $\geqslant 25$ in each time bin. With this approach, we sample variability time scales spanning hours to years. Additional details regarding the sample selection and data reduction can be found in Sobolewska *et al.* (2014).

Motivated by the reports of the log-normal X-ray flux distributions in the accreting black holes (e.g. Uttley *et al.* 2005), as well as in the TeV blazar PKS 2155-304 (H.E.S.S, Abramowski *et al.* 2010), we model the natural logarithm of the Fermi/LAT blazar γ-ray fluxes as a Gaussian variable.

4. Results

In order to evaluate the quality of the OU and mixed OU model fits to our light curves we investigated the distributions of fit residuals and the auto-correlation functions (ACF) of the fit residuals. If they resemble the standard normal distribution and the ACF of the white noise process, respectively, we conclude that a model fits the data well. In addition, we calculate the Deviance Information Criterion (DIC, Spiegelhalter *et al.* 2002) to assess which model is more successful in describing the blazar γ-ray light curves. A model with lower DIC is preferred to a model with higher DIC, and it is accepted that ΔDIC $\geqslant 10$ is a difference substantial enough to prefer the model with lower DIC.

We found that the light curves of blazars in our sample can be described either by the OU or mixed OU process, under the assumption that the natural logarithm of their γ-ray

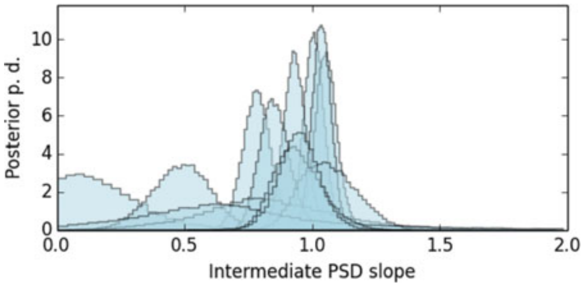

Figure 2. Posterior probability distributions of the PSD slopes, α (mixed OU process).

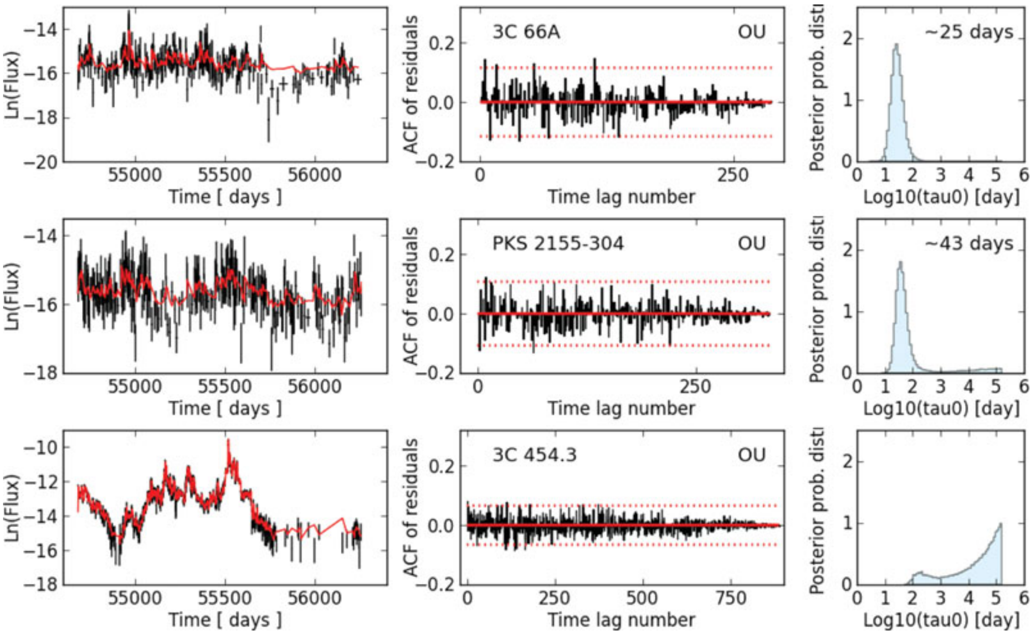

Figure 3. Left: Maximum likelihood OU model realization compared to the data. **Middle:** ACFs of model residuals and 95% confidence limits assuming a white noise process (dotted lines). **Right:** Posterior probability distributions of the OU characteristic time scale.

fluxed is a Gaussian variable. Light curves of 10 of 13 sources in our sample required the mixed OU process (see Fig. 1). For these sources we found only respective limits on the characteristic long and short time scales of variability, and we constrained the slopes, α, of their intermediate PSD (Tab. 1). The slopes, α, tend to cluster around unity (Fig. 2), and are flatter than the average PSD slopes found by Abdo *et al.* (2010) for bright FSRQs and BL Lac populations in the first 11 month of the Fermi/LAT data. Nakagawa & Mori (2013) studied PSD of individual blazars observed for the first 4 years of Fermi/LAT data. We found that the slopes derived using our stochastic method are in agreement with those of Nakagawa & Mori (2013) in 4 of 9 blazars present in both samples. We note, however, that our modeling covers much wider range of time scales, and thus deviations from the values found by Nakagawa & Mori (2013) might be expected.

In 3 of 13 sources we found that the mixed OU process does not provide fit improvement over the single OU process (Fig. 3). The derived posterior probability distributions allowed us to constrain the OU characteristic variability time scale, τ_0, in two BL Lac type sources, 3C 66A and PKS 2155-304 (Tab. 1; Fig. 3, right). We were not able to constrain τ_0 in the case of 3C 454.3. We note that in 3C 454.3 the mixed OU model also resulted in only a limit on the intermediate PSD slope value. Thus, we conclude that the PSD of the variability process exhibited by 3C 454.3 might be more complex than those of OU and mixed OU processes.

In 3C 66A and PKS 2155-304 the derived OU characteristic γ-ray variability time scales in the observer's frame (medians of the posterior probability distributions) are $\log(\tau_0/[\mathrm{day}]) = 1.39^{+0.43}_{-0.29}$ ($\sim$25 days, or $\sim$17 days in the rest frame) and $\log(\tau_0/[\mathrm{day}]) = 1.63^{+2.79}_{-0.35}$ ($\sim$43 days, or $\sim$38 days in the rest frame), respectively (the errors correspond to the 90% confidence regions). These values are not corrected for the Doppler boost due to the relativistic jet motion because it is not known whether these time scales correspond to the intrinsic jet processes, or result e.g. due to a jet modulation caused by an external process. These are the first BL Lac type sources for which a γ-ray characteristic variability time scale has been reported.

5. Discussion

Many previous blazar γ-ray variability studies searched for the shortest variability time scales in order to constrain the size of the γ-ray blazar emitting region (e.g. Saito *et al.* 2013). A formalism relying on the flux-doubling and flux-halving time scales was used to define the γ-ray flares and study their properties (e.g., Nalewajko 2013). Instead, in this work we investigated whether the γ-ray blazar light curves are consistent with a stationary stochastic process (similarly to the case of the optical and X-ray AGN light curves studied by Kelly *et al.* 2009, 2011), and we and searched for the characteristic variability time scales related to the bends in the underlying PSD of the considered processes. In our approach the higher flux states associated commonly with the γ-ray flares would be manifestations of the same stochastic process that produces the bulk of the lower amplitude variability.

While the single OU or the mixed OU processes could be applied successfully to the Fermi/LAT γ-ray blazar light curves, we note that these processes are characterized by relatively simple PSDs, featuring one or two bends separating the power-law like PSD sections. However, it is likely that the underlying blazar γ-ray PSDs are more complicated, e.g. they might feature deviations from the power-law shape, or decrease faster than f^{-2} at the shortest time scales. Thus, we are in the process of applying a CARMA process (Continuous Auto-regressive Moving Average process, Kelly *et al.* 2014) to our γ-ray blazar light curves. The PSD of the CARMA process is composed of a sum of Lorentzian functions with the centroids, widths and normalizations being free parameters, that can be computed using the auto-regressive and moving average coefficients inferred from the data. Thus, the CARMA process offers flexibility required to model relatively complicated PSD shapes.

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