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New statistical results on the optical IDV data of BL Lac S5 0716+714

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Abstract This paper reports on the statistical behavior of the optical Intraday Variability of BL Lac S5 0716+714. Available Intraday Variability data in the optical are tested to see whether or not the magnitude is lognormally distributed. Our results consistently indicate that this is not the case. This is in agreement with a previous discussion about data for the same object but in a different observational period. Simultaneously, the spectral slope of the light curves is calculated. The implications of these findings on models that describe both the location and source of Intraday Variability are presented.

Key words: radiation mechanisms: non-thermal — BL Lacertae objects: individual: S5 0716+714

1 INTRODUCTION

BL Lac S5 0714+716 is an object with confirmed and documented variability in all wavelengths and on a wide interval of timescales. Theoretical tools have managed to satisfactorily explain most of the variability behavior. However, there is a wide debate regarding the source of intraday variability (IDV, variability in flux on a timescale of a few hours) detected in the light curves (LCs) of such objects. The problem is at least twofold: where is this source *located*, with possible answers being the disk or the jet; and, more profoundly, what is the exact *physical mechanism* able to produce such fast variability? The answer to this final question is still incomplete, but there seems to be an agreement that the magnetic field is involved in some way. In fact, as shown in other astrophysical applications (e.g., Lazarian & Vishniac 1999; Ohsuga et al. 2005) and somewhat successfully for these types of objects (Mocanu et al. 2014), a model based on stochastic magnetic field reconnection provides many of the necessary properties that fit models to observations.

Bringing some light to both of these issues must involve data analysis, modeling and reproducing (at least partially) the statistical properties exhibited by the LCs, e.g. the power spectral distribution (PSD) and the presence/absence of a linear flux versus root mean square relation (the rms-flux or, equivalently, the lognormal distribution of the LCs)[1]. To the best of our knowledge, this is the first

[1] From the point of view of their statistical behavior, magnitude and flux are used interchangeably due to the fact that for the data considered here, they are related through a linear relation.

simultaneous analysis of the spectral slope combined with testing a hypothesis for a lognormal distribution; we also analyze a set of simulated LCs with identical minimum, maximum, mean and variance for each of the observed LCs. These properties are discussed in connection to both the location and nature of IDV in the next subsection; these general considerations are applied to observational data for BL Lac S5 0716+714 (Sect. 2) and the implications of the results are described in Section 3.

1.1 Location and Nature of the IDV Source

There are two possible strong (theoretical) candidates for the location of the source of IDV: the disk (e.g., Hawley et al. 1996; Mineshige & Yonehara 2001) or the jet (e.g., Chandra et al. 2011). Both theories have their advocates, and present both advantages and disadvantages. The advantage of both, from our point of view, is that in both situations, a magnetic field is present.

The continuum emission from accretion disks depends on the mass of the central black hole, such that low mass black holes produce continuum X-ray emission and supermassive black holes (such as the object studied here) would produce a continuum in the optical (Czerny 2002; Frank et al. 2002). Optical IDV is seen as variations of output magnitude superimposed on the continuum emission (e.g., Gaskell & Klimek 2003; Krolik 1999).

The data analysis in Section 2 can help in at least two frameworks and is based on the following (explained in more detail in Mocanu & Sándor 2012):

(1) Historically, the optical/UV and X-ray continua were thought to be partially connected through reprocessing in the disk (Kawaguchi et al. 1998; Shakura & Sunyaev 1973; Young et al. 2010)[2] and X-ray variability does exhibit a linear rms-flux in its fast variability (Uttley et al. 2005; Gaskell & Klimek 2003)[3]. Does the reprocessing change the distribution from lognormal to something else?
(2) Short timescale variability in X-rays (for low mass black holes) may be explained by the disk model that uses propagating fluctuations from Lyubarskii (1997), which also naturally explains both the PSD of the LCs and the linear rms-flux relation (Arévalo et al. 2008; Scaringi et al. 2012). Conversely, it is believed that the existence of a linear rms-flux relation suggests that the variability originates in the accretion flow (Arévalo & Uttley 2006).

We have recently proposed (Mocanu & Sándor 2012) that a valuable argument in this debate might be offered by analyzing whether or not optical IDV in AGNs shows a linear rms-flux relation or, equivalently, to check if the LCs are lognormally distributed. For our previous set of data (Mocanu & Marcu 2012; Mocanu & Sándor 2012), fast X-ray variability for this BL Lac did exhibit a linear rms-flux, but optical IDV did not.

As observations show that the X-ray and optical/UV flares are nonstationary and nonlinear, power spectral analysis alone does not adequately represent all the information contained in the LC (Gaskell & Klimek 2003; Uttley et al. 2005 give a comprehensive discussion of Self Organized Criticality, PSD and the rms-flux relation for the X-ray variability), so a joint magnitude distribution and PSD analysis are required.

The simplistic approach described above can fail and may not give conclusive answers if the approach to data analysis is not as thorough as possible. In light of continuously developing models, it might be that IDV is produced in the disk and the process leading to IDV cannot be accounted

[2] However, it has been shown for particular AGN objects that the optical and X-ray are not connected through reprocessing, neither for long timescale variability, continua nor IDV (McHardy et al. 2004; Gaskell & Klimek 2003 and references therein).

[3] As an interesting side note, optical variability on longer timescales (tens of days to years) does exhibit a linear rms-flux relation (Gaskell & Klimek 2003).

for by the propagating fluctuations model. It is thus obvious that a detailed analysis and discussion of statistical properties of the data are interesting on their own. Comparisons of statistical data properties (e.g. PSD, linear/or-not rms-flux, flux distribution) associated with different objects, like supermassive black holes, stellar mass black holes and the Sun itself, show that LCs may share some statistical properties but may also show unique behaviors (Zhang 2007).

Analysis of data from BL Lac S5 0714+716 has shown that variations in this source are stochastic (Azarnia et al. 2005; Carini et al. 2011; Leung et al. 2011; Mocanu & Marcu 2012) and stochastic simulations can reproduce some of the characteristics in the data (Harko & Mocanu 2012; Harko et al. 2014; Mocanu et al. 2014; Xiong et al. 2000; Kawaguchi et al. 2000; Mineshige et al. 1994).

2 DATA ANALYSIS

Data analysis of BL Lac S5 0714+716 has been previously discussed in Wu et al. (2007) (examples of LCs are shown in Figs. 1 and 2 left). Observations have been carried out between 2006 January 1 and February 1. We discuss a set of 12 LCs that each have at least 100 data points. The object was very active during this period, showing variations with amplitudes larger than 0.1 mag and being as large as 0.3 mag.

With a value of $z = 0.31$ for the redshift of this object (Nilsson et al. 2008) and a mass of $M = 10^8 M_\odot$ (Poon et al. 2009) for the central object, the extension of the emission region can be expressed in gravitational radii as $\Delta r = 1.5 \times 10^{-3} \Delta t$, where Δt is the observed variability timescale. For $\Delta t = 1$ hour, the extension of the emission region is $5.5 r_{\rm g}$.

The procedure was previously used and described in Mocanu & Sándor (2012). We tested if the LCs are lognormally distributed (e.g. Figs. 1 and 2 right) by using the chi-square goodness of fit test. The constraint of having at least five members in each bin was obeyed at all times, forcing us to split the data into only eight bins. The same χ^2 statistical test was produced for a simulated LC with a lognormal distribution (Fig. 3). The simulated LC was constructed having the same number of points as the observational data, as well as the same mean and variance.

The main results of the analysis are given in Table 1. The first and second columns provide the observation date and the band. The third column contains the value of the χ^2 statistical test for the experimental data, with the hypothesis that it is lognormally distributed and the fourth column shows the statistics from the time series simulations. The fifth column contains the value of the spectral slope and the sixth the output of the Bayesian statistical value of the null hypothesis for the data; the seventh and eighth columns give corresponding values for the simulated LCs.

Table 1 Results for testing the hypothesis that the time series are lognormally distributed, with $\chi^2_{\rm ref} = 11.07$, eight bins and five degrees of freedom. Results are shown for the spectral slope under the hypothesis that the time series have a PSD $\sim f^{-\alpha}$.

Date	Band	χ^2 (obs)	χ^2 (sim)	α (obs)	$p_{\rm B}$ (obs)	α (sim)	$p_{\rm B}$ (sim)
2453736	B	28.589	8.251	1.398[0.104]	0.539	–0.002[0.117]	0.57
2453736	V	73.706	8.31	1.739[0.101]	0.957	0.219[0.127]	0.903
2453744	V	12.343	8.32	1.528[0.098]	0.763	–0.311[0.141]	0.072
2453742	R	27.569	7.753	1.792[0.101]	0.51	–0.077[0.139]	0.021
2453743	R	7.741	7.988	1.382[0.102]	0.226	–0.043[0.115]	0.653
2453761	R	17.735	8.056	1.929[0.168]	1	0.076[0.157]	0.657
2453761	V	16.554	7.533	1.476[0.130]	0.855	–0.042[0.179]	0.464
2453737	V	72.829	7.896	1.621[0.099]	0.117	0.070[0.123]	0.228
2453743	V	7.671	7.852	1.309[0.098]	0.171	0.026[0.122]	0.226
2453737	R	74.175	7.967	1.675[0.098]	0.24	–0.055[0.132]	0.248
2453744	R	35.044	7.828	1.536[0.1]	0.344	–0.099[0.13]	0.051
2453760	V	28.647	8.335	1.321[0.098]	0.102	0.125[0.121]	0.772

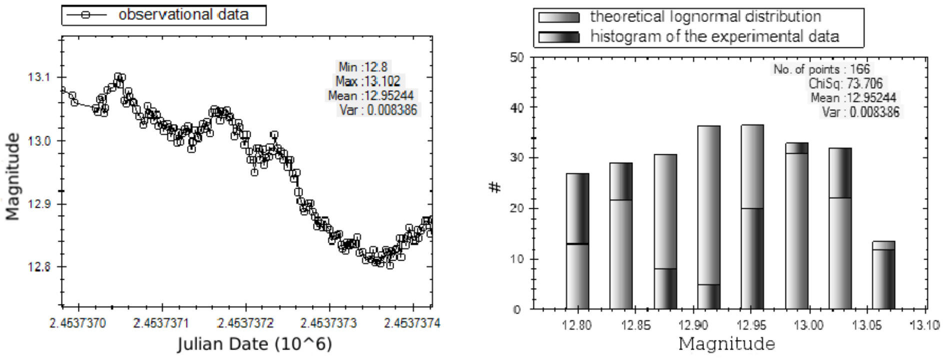

Fig. 1 *Left*: Observed LC. *Right*: Magnitude distribution of the LC with the corresponding theoretical lognormal distribution superimposed. Data taken during JD 2453736, in the V filter.

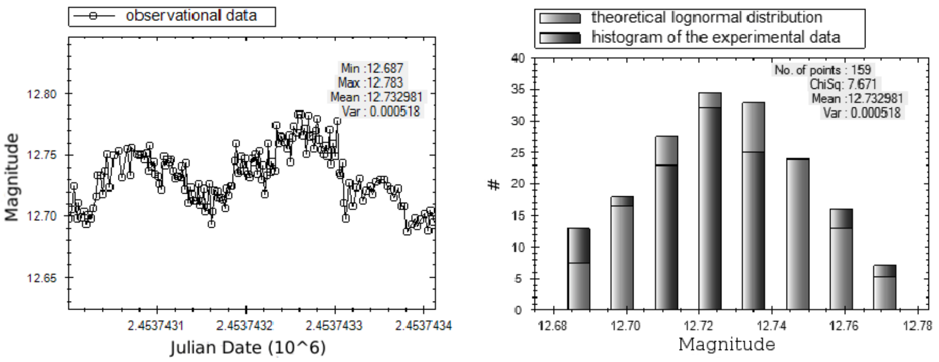

Fig. 2 *Left*: Observed LC. *Right*: Magnitude distribution of the LC with the corresponding theoretical lognormal distribution superimposed. Data taken during JD 2453743, in the V filter.

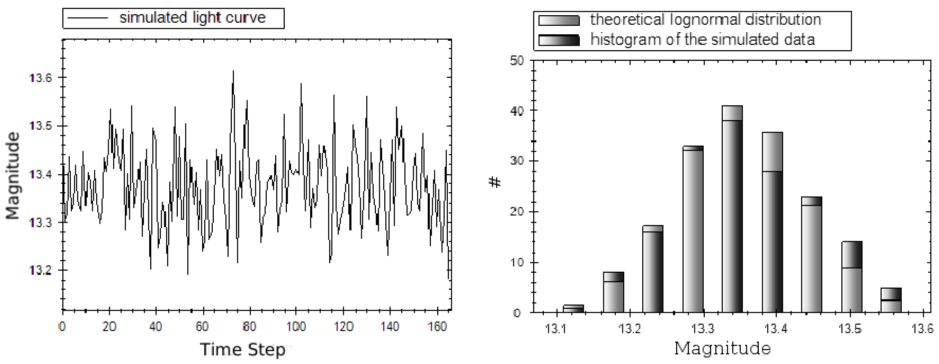

Fig. 3 *Left*: Simulated LC for a lognormally distributed process. *Right*: Magnitude distribution of this LC with the corresponding theoretical lognormal distribution superimposed.

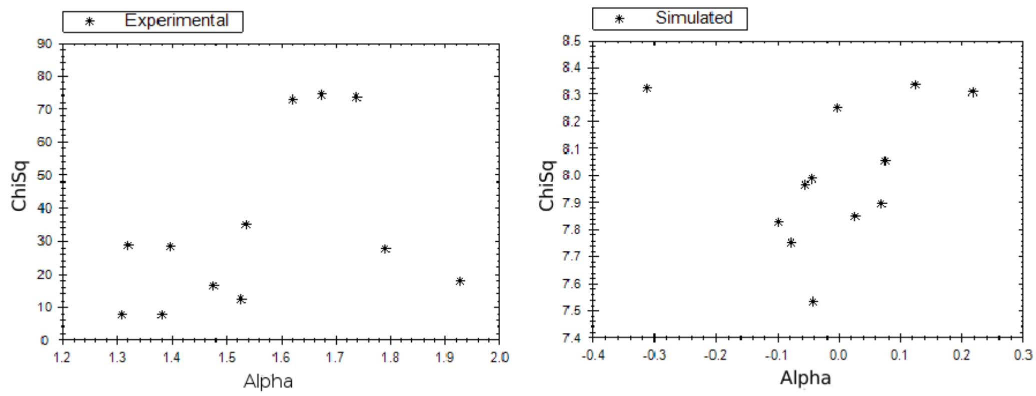

Fig. 4 Spectral slope vs. calculated value for the χ^2 test that is applied to the observed LCs (*left*) and simulated LCs (*right*).

The spectral slope α and the Bayesian statistic $p_{\rm B}$ are calculated with the R software package using the Bayes script that is described in detail by Vaughan (2010). The value of the spectral slope α is calculated by mediating over many realizations of a process with the same characteristics as the LC, which is taken as input, with realizations obtained through Monte Carlo simulations. The Bayesian probability assesses the correctness of the assumption, i.e. if $p_{\rm B}$ is close to 1, then the assumption that the emission process behaves in a way to produce a luminosity with PSD $\sim f^{-\alpha}$ is correct. For details about the technical procedure, see Vaughan (2010).

The analysis of the results in the table clearly shows that the data we analyzed do not obey a log-normal distribution. Moreover, it can be seen that the values needed for α to produce an acceptable χ^2 are completely different from the observed ones (Fig. 4).

3 CONCLUSIONS

The spectral slope and the possibility that the optical IDV of BL Lac S5 0716+714 is lognormally distributed was analyzed. Based on this set of data and on a set analyzed in a previous work (Mocanu & Marcu 2012, Mocanu & Sándor 2012), we can conclude that it is more probable that the hypothesis of a lognormal distribution is false. A quick judgement of this result might lead to the conclusion that this fact is an indication of IDV not being located in the disk. However, there is no evidence that a lognormal distribution is a necessary and sufficient condition, but rather just eliminates some of the competing models as candidates for IDV. Although the discovered rms-flux in X-ray cannot be obtained by standard shot noise models (although they do reproduce some PSD features) (Uttley & McHardy 2001), these types of models are thus not excluded for fast optical variability.

Based on the wealth of data, interpretation, models and leaving room for uncertainties inherent in all scientific endeavors pertaining to distant galaxies, this result tells us at least two things: from a numerical point of view, LCs with more data points are needed such that statistical analysis can reproduce conditions necessary for the central limit theorem to hold; from a physics-based point of view, better models are needed such that the wealth of statistical characteristics of IDV LCs can be reproduced as accurately as possible within one single framework.

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