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Optical variability of Active Galactic Nuclei from Catalina Surveys data

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Abstract. The Catalina Real-Time Transients Survey (CRTS) has observed a large fraction of the sky ($\sim 33000 \text{ deg}^2$), detecting more than 500 million objects several times, so providing a statistically consistent database of multi-epoch observations of various Galactic and extragalactic sources. Therefore, it is particularly suitable to perform variability studies over different timescales. The analysis of active galactic nuclei (AGN) flux variations provides an invaluable insight on these sources since variability encodes the underlying physics of the emitting regions. In this context, we present an optical variability analysis based on a statistical sample of AGN derived from the crossmatching of a preexistent multi-wavelength based catalogue (Multi-Epoch X-ray Serendipitous AGN Sample 2, or MEXSAS2) with the Catalina Surveys Data Release 2 (CSDR2). Visual inspection of the light curves and a novel estimate of the photometric error associated to the Catalina Sky Surveys have been mandatory to obtain a refined sample of 400 quasars widespread over a large interval of redshift ($0.1 < z < 3.4$) and bolometric luminosity ($10^{45} \text{ erg/s} \lesssim L_{\text{Bol}} \lesssim 10^{48} \text{ erg/s}$). We exploit the structure function (SF) method, which works in the time domain, to investigate the short (few days) to long term (up to ~ 10 years) variability properties of our sample. Our variability analysis suggests a possible underestimate of the photometric errors, which strongly affect the structure functions.

1. Introduction

Active galactic nuclei (AGN) are extremely powerful sources, whose luminosity can reach (for the most energetic ones) a value of $\sim 10^{48} \text{ erg/s}$ (e.g. [1]). AGN are located at the centre of many galaxies, where they are powered by accretion processes onto a super-massive black hole (SMBH), whose typical mass lies between 10^6 and $10^{10} M_{\odot}$. The emission comes from a very compact region, which in several cases is smaller than $\sim 10^{15} \text{ cm}$ (e.g. [2, 3]). Variability studies provide insights into the physical mechanisms behind emission processes (e.g. [4, 5, 6]) as well as a description of the geometry and size of the emitting regions (e.g. [7, 8, 9]). In order to do so, they require repeated observations of the same sources at many different epochs. Therefore, we present our variability analysis of an AGN sample (see Section 3) based on the Catalina Surveys, which fulfil the above requirement. The paper is organised as follows. In Section 2 we present a brief description of the surveys. Section 3 describes the selection criteria used to extract our AGN sample. In Section 4 the structure function (SF) is introduced as a powerful tool to analyse variability and we discuss the results of its application on our AGN sample. In Section 5 we report on correlations between the variability parameters of such sample, calculated



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by means of the SF, and characteristic physical quantities of AGN. Ultimately, in Section 6 we discuss and summarise the results.

2. The Catalina Surveys

In 1998 Steve Larson founded the Catalina Sky Survey (CSS) which, soon after, joined the NASA's Near-Earth Object Observation (NEOO) program. From 2007, the CSS has been assisted by the Catalina Real-Time Transients Survey (CRTS) [10, 11] which was developed in order to search for transients. Since 2013 both surveys could rely on three telescopes [12], whose detections are included in the currently up-to-date data release: the Catalina Surveys Data Release 2 (CSDR2)¹. This catalogue lists photometric measurements of ~ 500 million objects and several extragalactic sources – such as AGN – are included among them. In order to maximise the amount of incident light, the magnitudes are measured by means of unfiltered photometry. CSDR2 is suitable to analyse the variability of individual objects, since each source in this catalogue has been observed several times.

3. Sample selection

We chose an AGN sample, called Multi-Epoch X-ray Serendipitous AGN Sample 2 (MEXSAS2), whose variability properties had been previously investigated in the X-ray band [13, 14]. This sample included 9735 detections associated to 3366 different sources. Hence, the aim of the present work is to perform an individual variability analysis of the sources included in MEXSAS2 which have an optical counterpart in CSDR2. It is also important to underline that all the MEXSAS2 objects have an optical match in the Sloan Digital Sky Survey (SDSS) Quasar Catalogs, DR7Q [15] and DR12Q [16]. Furthermore, measurements of interesting physical quantities (e.g. bolometric luminosity, Eddington ratio, black hole mass) related to such sources are also available [17, 18]. We performed a crossmatch between the objects included in MEXSAS2 and CSDR2 within a radius of 3 arcsec in coordinates, imposing that the difference between the average magnitude reported by CSDR2 and SDSS was smaller than 0.8 mag. After the crossmatching procedure, we obtained a sample of 340051 observations of 2070 AGN taken between April 2005 and January 2014.

4. Data analysis

We adopted the SF as variability estimator. Its definition is given by the following expression (e.g. [19]):

$$\text{SF}(\tau) = \sqrt{\langle [m(t+\tau) - m(t)]^2 \rangle - \sigma_{noise}^2}. \quad (1)$$

The SF accounts for the mean squared difference between the magnitude m of the object as measured at two epochs separated by a time lag τ (in the rest frame of the source), corrected for the contribution of the joint photometric uncertainties, $\sigma_{noise}^2 = \langle \sigma^2(t) + \sigma^2(t+\tau) \rangle$. Fig. 1 shows an example of a SF of an individual source included in our sample. In order to compare our results with those from previous studies (e.g. [20]) we modelled our SF as a power law:

$$\text{SF}(\tau) = C \left(\frac{\tau}{1 \text{ yr}} \right)^a, \quad (2)$$

which is usually recast as:

$$\log \text{SF}(\tau) = b + a \tau. \quad (3)$$

¹ <http://nessi.cacr.caltech.edu/DataRelease/>

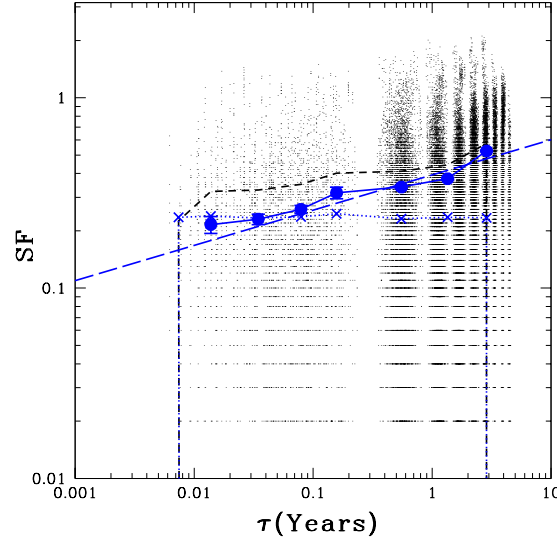


Figure 1. SF associated to the source MEXSAS2 239 and properly corrected for the photometric error (blue circles). The uncorrected SF and the contribution of the photometric uncertainty are shown by the dashed black and dotted blue lines, respectively. Blue long-dashed line represents the least-squares fit to the power law of Eq. 3. Small black dots refer to the individual variations between each couple of epochs in the light curve. The time lag τ is evaluated in the rest frame of the source.

The distribution of the variability parameters a and b (respectively called slope and normalisation parameter) highlighted the following issue. The SF has always been witnessed as an increasing function of the time lag (e.g. in the optical [21, 22]; in the X-ray [13, 23]). On the contrary, in the present case, we found that several sources displayed a flat SF power law ($a \sim 0$), which is a controversial result. Since also the contribution of the photometric error is not significantly varying over time, we hypothesised we were measuring variations dominated by the error – which could reproduce such flat behaviour – instead of those intrinsic to the sources.

In the literature, several authors asserted that Catalina suffered from inaccurate photometry (e.g. [24, 25]). Among them, Graham et al. (2017) [26] introduced a multiplicative corrective factor for the photometric error which we implemented in our analysis.

Peters et al. (2015) [20] computed the individual SFs for a statistically significant AGN sample, using data from SDSS Stripe 82 (S82). A subsample of these sources (146) are found to be in common with our sample, allowing us to perform a comparison between the SFs computed from the two datasets. Although the data in S82 are characterised by smaller photometric errors with respect to CSDR2, the SFs corrected for the uncertainties should be characterised by similar behaviours. This occurs for many sources in our selected subsample. Nevertheless the CSDR2 SFs of some objects remain flat, as shown by the case in Fig. 2.

The distribution of the variability parameters obtained accounting for the correction by Graham et al. (2017) [26], is displayed in Fig. 3. It can be seen that a large fraction of values still lay around $a \sim 0$. The flatness of the SFs shown in Fig. 2 and Fig. 3 infers that the error is still underestimated: a more suitable correction is suggested.

Ultimately, after the removal of some outliers in the light curves, we suggest that the best estimate for the uncertainties may consist in a 20% enhancement of the corrective factor by Graham et al. (2017) [26]. Increasing the uncertainties allowed to compute only 400 SFs.

5. Correlations

The MEXSAS2 catalogue included information about physical quantities of AGN such as bolometric luminosity, Eddington ratio, black hole mass and redshift [17, 18].

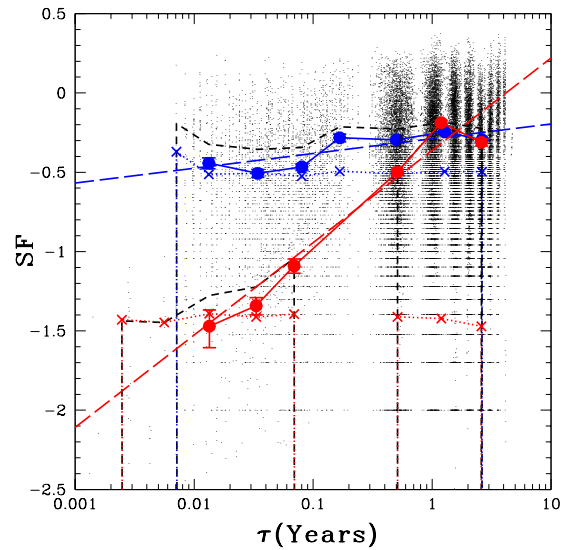


Figure 2. Comparison between the SFs of the source MEXSAS2 131 computed using data from CSDR2 (blue solid line and circles) and S82 (red solid line and circles). Even if the contribution of the photometric error in CSDR2 (blue dotted line) has been appropriately subtracted, the corrected SF (blue solid line) remains quite flat. Red dotted line represents the much smaller contribution of the errors from S82. Small black dots refer to the individual variations between each couple of epochs in the light curve. The time lag τ is evaluated in the rest frame of the source.

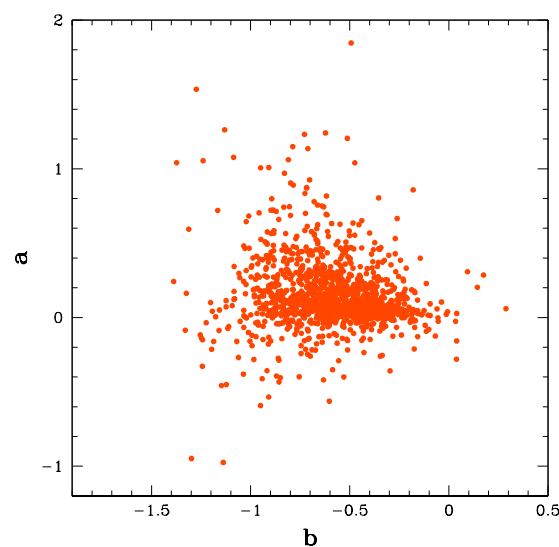


Figure 3. Distribution of the variability parameters after the implementation of the corrective factor by Graham et al. (2017) [26].

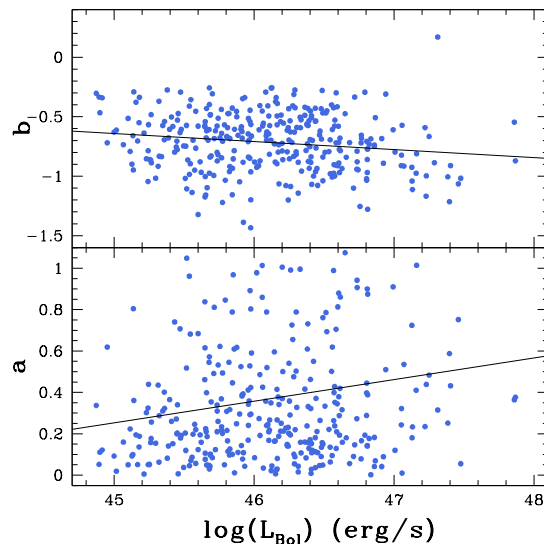


Figure 4. Correlations between variability parameters and bolometric luminosity, L_{Bol} for our final AGN sample derived by CSDR2 data. Upper panel: normalisation parameter b , correlation coefficient $r = -0.15$, probability $p(> |r|) = 0.005$; lower panel: slope parameter a , $r = 0.17$, $p(> |r|) = 0.002$.

We looked for possible correlations between these quantities and the variability parameters. This analysis has been carried out on the catalogue of 400 sources derived by CSDR2 data. The results were generally in agreement with the literature. For instance, the variability normalisation appears to be anti-correlated with the bolometric luminosity, as already verified in several previous studies (e.g. [27, 28, 29, 30]). The variability study about the slope parameter of the SF represents a completely novel approach. As an example, from our work it is emerging the evidence for a possible increase of the SF slope with L_{Bol} (see Fig. 4).

Unfortunately, despite the corrections, the results involving CSDR2 data are still affected by large photometric errors and should be considered with caution.

6. Conclusions

This work proves that the large sampling in CSDR2 may allow to compute detailed individual SFs. However, the large photometric errors dramatically affect such analysis. Since several SFs are still quite flat – after several corrections – it is possible that the uncertainties may be still underestimated. In the future we propose to lower these errors by binning the data in small intervals of time and making use of the Catalina Surveys Data Release 3 (CSDR3), which should rely on a much more accurate photometry [31].

Acknowledgments

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