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Optical Variability of Active Galactic Nuclei

*Szymon Kozłowski**

Astronomical Observatory, University of Warsaw, Warsaw, Poland

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1. INTRODUCTION

Variability studies of active galactic nuclei (AGNs) typically use either power spectral density (PSD) and structure function (SF) analyses or direct modeling of light curves with the damped random walk (DRW) and the continuous autoregressive moving average (CARMA) models. A fair fraction of research publications on the subject are flawed, and simply report incorrect results, because they lack a deep understanding of where these methods originate from and what their limitations are. For example, SF analyses typically lack or use a wrong noise subtraction procedure, leading to flat SFs. DRW, on the other hand, can only be used if the experiment length is sufficient, at least ten times the signal decorrelation time scale τ, and if the data show the power-law SF slope of $\gamma \equiv 0.5$.

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***Correspondence:**
Szymon Kozłowski
simkoz@astrouw.edu.pl

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2. STRUCTURE FUNCTIONS

The structure function (SF) analysis is a model-independent technique of converting an active galactic nucleus (AGN) light curve into a different space, the variability amplitude–timescale space. The basic approach behind the SF analysis is as follows. Data points y_i in an AGN light curve are, in the simplest case, a sum of the variable signal s_i (with the variance σ_s^2) and the observational noise n_i (with the variance σ_n^2), so $y_i = s_i + n_i$. SF originates from simple mathematical properties of the covariance of the light curve (index i) with a shifted copy of itself (index j) by the timelag $\Delta t = t_i - t_j$, via (MacLeod et al., 2010; Kozłowski, 2016b)

$$\mathrm{SF}(\Delta t)^2 = 2\left(\sigma_s^2 - \mathrm{cov}(s_i, s_j)\right) + 2\sigma_n^2, \tag{1}$$

where SF(Δt) is typically measured from data as

$$\mathrm{SF}(\Delta t)^2 = \frac{1}{N_{\Delta \mathrm{t\ pairs}}} \sum_{i=1}^{N_{\Delta \mathrm{t\ pairs}}} (y_i - y_j)^2. \tag{2}$$

In order to measure the true AGN variability, so in fact $\mathrm{cov}(s_i, s_j)$ in Equation (1), one needs to subtract the full noise term ($2\sigma_n^2$) from the SF in Equation (2). This is either rarely done in recent works or done incorrectly, as commonly only a fraction of the noise term (σ_n^2) is subtracted. This leads to flat power-law SF slopes of $\gamma = 0.1$–0.4 at short timescales Δt ($\mathrm{SF}(\Delta t) \propto \Delta t^{\gamma}$) (e.g., Vanden Berk et al., 2004; de Vries et al., 2005), but when correctly measured, the SF slope in optical is significantly steeper $\gamma = 0.55 \pm 0.08$, based on ~9,200 SDSS AGN from Stripe 82 (Kozłowski, 2016b) and $\gamma \approx 0.45$ in mid-IR (Kozłowski et al., 2010a, 2016). An equally important variability observable to the SF slope is the decorrelation timescale τ, a timescale at which the SF changes slope from the red noise ($\gamma = 0.5$) to the white noise ($\gamma = 0.0$). It seems to be about one year rest-frame, again based on ∼9,200 SDSS AGN from Stripe 82 (Kozłowski, 2016b). I recently proposed a new method of the measurement of the unbiased decorrelation timescale τ from SFs (Kozłowski, 2017a). Another SF observable is the AGN variability amplitude measured at 1 year (rest-frame) with the value of 0.20 ± 0.06 mag in optical bands, while the asymptotic variability amplitude at long timescales ($\Delta t \gg \tau$, so $\Delta t \gg 1$ year rest-frame) is 0.25 ± 0.06 mag (Kozłowski, 2016b). The SF amplitude at 1 year may be affected, while the asymptotic variability amplitude is not, by the bias due to the unknown underlying stochastic process for short datasets (Kozłowski, 2017a).

3. THE DAMPED RANDOM WALK

AGN light curves can be modeled and interpolated using the damped random walk (DRW) stochastic process. DRW modeling (Kelly et al., 2009; Kozłowski et al., 2010b; MacLeod et al., 2010) by definition assumes an exponential covariance matrix of the signal of the form

$$\mathrm{cov}(s_i, s_j) = \sigma_s^2 e^{-\frac{|t_i - t_j|}{\tau}}, \tag{3}$$

that again by definition produces a fixed SF power-law slope of $\gamma \equiv 0.5$ at timelags $\Delta t = t_i - t_j$ shorter than the signal decorrelation timescale τ (Kozłowski, 2016b). If the variability signal is due to a different stochastic process, where the SF slope is shallower/steeper than $\gamma = 0.5$, DRW will obtain a reasonable fit, however, it will report biased measurements (Kozłowski, 2016a). As of now, there is no statistical correction available to this problem, however, using the information on the SF/PSD slope one can modify the DRW model covariance matrix (Equation 3) and model the light curves with the modified DRW model to obtain correct parameters. DRW should be used to model an AGN light curve if one is convinced that the SF slope for a light curve is $\gamma = 0.5$ (or equivalently the PSD slope is -2). There is another issue with DRW: if the light curve is shorter than 10τ (∼10 years rest-frame), it will simply report meaningless variability parameters (Kozłowski, 2017b). DRW is the simplest of the CARMA models [i.e., DRW $\equiv$ CARMA$(1, 0)$], therefore the whole CARMA model family is plausibly affected by biases or problems reported above.

4. CONCLUSIONS

Constraining the SF, PSD, and DRW (or more generally the Gaussian processes) parameters typically require long and well-sampled AGN light curves. Such tight constraints may soon be available from the OGLE Sky Survey (Udalski et al., 2015), that has been monitoring the sky for 25 years, and in particular from its 20-year-long monitoring of nearly 1,000 AGNs (each with ∼1,000 epochs), discovered mostly by the Magellanic Quasars Survey (Kozłowski et al., 2013). Similarly to the results from the SDSS Stripe 82, preliminary results from OGLE point to the mean SF slope $\gamma \gtrsim 0.5$. For sparsely sampled or short light curves some corrections to improve biases in PSD/SF/excess variance measurements are available (Vaughan et al., 2003; Allevato et al., 2013), although in a statistical (ensemble) sense, rather than for individual objects.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and approved it for publication.

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