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Dissertation Summary

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ABSTRACT

The dissertation summary....

1. SCIENTIFIC CONTEXT

1.1. *Quasars as distant, powerful Active Galactic Nuclei*

Quasars are some of the most luminous sources of radiation in the Universe. Termed initially as Quasi-Stellar Objects, they appear as unresolved stellar-like point sources when observed with ground-based angular resolution (of the order an arcsec). However, spectroscopic observations show non-thermal radiation unlike any star. In addition, high angular resolution observations, such as the Hubble Space Telescope imaging, reveal a faint glow of a host galaxy around the intense still-unresolved source of light. The host galaxy's faint glow is so much dimmer and more diffuse than the quasar light that it took decades after the serendipitous discovery of quasars by Maarten Schmidt in 1963 (Schmidt 1963; Richards et al. 2009) to reliably prove that quasars "live" in galaxies (Hooper et al. 1997; Boyce et al. 1999; Lehnert et al. 1999). Early on it was realized that the main source of quasar light is a hot accretion disk of material infalling onto a supermassive black hole (SMBH) in the center of a host galaxy (Oke 1965; Burbidge 1967). Active Galactic Nuclei (AGN) are galaxies with signs of nuclear activity due to accretion of gas onto the central SMBH (Netzer 2013). When the Universe was denser at earlier times (at higher redshifts), the mergers of galaxies were more frequent, and the supply of gas higher - thus we would expect that the AGNs of the past (or earlier times, higher redshifts), were more powerful than those at work "today", or in the nearby universe. This is indeed the case - we find that quasars are just much more distant, more luminous AGNs. It is only the sheer distance (and intrinsic brightness) that resulted in different features observed at first (eg. point-like accretion disk emission for a quasar, rather than the extended emission from AGN's radio lobes).

Quasars are very interesting objects in their own right. An accretion disk is an extreme environment: it is a disk of viscously heated matter inspiralling onto an SMBH (Ruan 2017). The disk by itself is merely a few times bigger than the solar system - Mudd et al. (2017) finds with reverberation mapping that disk sizes for their sample of quasars are between 1-10 light days, that is ten to a hundred times the size of the orbit of Pluto, at 0.23 light days. The accretion disk due to a relatively small size compared to the host galaxy cannot be resolved with even the largest currently operating or planned telescopes (0.01 miliarcsec at 20 Mpc is beyond the reach of James Webb Space Telescope or European Extremely Large Telescope, Gardner et al. (2006); Diolaiti et al. (2015)). Therefore study of the the accretion disk is achieved by microlensing (Agol & Krolik 1999; Jiménez-Vicente et al. 2012) and reverberation mapping (Jiang et al. 2017; Mudd et al. 2017). Emission from the accretion disk overwhelms all the light from the stars of the host galaxy, but with sufficient light collecting area and exposure it is possible to image the host too (Hutchings et al. 2002; Kotilainen et al. 2013; Falomo et al. 2014; Liuzzo et al. 2016; Bayliss et al. 2017).

1.2. *Scientific uses of quasars*

Quasars are an excellent probe of the evolution of the universe over time. Present across vast range of distances (redshifts), quasars are witnesses to the conditions in the universe from the earliest times of first galaxies, to later galaxy mergers. The distribution of quasars peaks at the redshift $\approx$2, and they have been seen all the way from redshift 0.1 to 7.5 (Pâris et al. 2017; Bañados et al. 2018). Before it reaches us, quasar light passes through other galaxies and clouds of gas, which leave their imprint in the form of absorption lines and troughs. For this reason quasar spectra are useful for studies of the intergalactic medium (Prochaska et al. (2014) and references therein), He II reionization history (Khrykin et al. 2017), Damped Lyman α Absorbers (Wolfe et al. 2005; Murphy & Bernet 2016; Parks et al. 2018). Quasars quite literally shine light on the epoch of reionization - the moment when the universe, full of neutral Hydrogen and Helium from the Big Bang, became ionized (Glikman et al. 2011; Masters et al. 2012; Ross et al. 2013). Counting the number of quasars as a function of luminosity yields the Quasar Luminosity Function (QLF), which is a diagnostic of the SMBH growth rate, quasar activity, and the evolution of the galactic Initial Mass Function (Schawinski 2012; McGreer et al. 2013; AlSayyad 2016).

1.3. *Quasars - objects variable on multiple timescales*

Given the inherent dynamics of the quasar phase of galaxy's lifetime, it makes sense that as the gas supply to the SMBH environment varies, the brightness should change over time both for an accretion disk, as well as any absorption/emission features caused by the orbiting clouds (Stern et al. 2017; Schawinski et al. 2015). Since for a quasar the emission from the accretion disk is dominant compared to the stellar light from the host galaxy, we can assume that all the coherent variability in the quasar light curve is related to the accretion disk variability. Quasar brightness varies over timescales from millions of years to hours, with variability on each timescale tied to a different physical mechanism (Sartori et al. 2018). The longest timescales of millions of years (postulated but not directly measured) correspond to the changes in overall accretion pattern, for instance as the galactic merger that started the quasar phase progresses. Indeed, it is now thought that quasars are just an episode (or multiple episodes) in life of almost any galaxy (Alexander & Hickox 2012; Kormendy & Ho 2013). Progressing to shorter (more directly measurable) timescales of years, quasar brightness may change due to a variable strength of an underlying continuum emission, tied to the amount of available gas (see eg. Changing-Look AGNs, and discovered recently Changing-Look Quasars - Ruan et al. (2016); MacLeod et al. (2016); Graham et al. (2017)). There is also variability on medium timescales of weeks to months that can be easily observed in a quasar light curve. Historically it was variability on these medium timescales in the optical light that first hinted at the relatively small size of the region emitting the light (if the brightness of an entire disk changes, two parts of the disk must be separated by less than the light travel time - Mudd et al. (2017); Blackburne et al. (2011); Morgan et al. (2010)).

1.4. *Mathematical description of quasar light curves*

Quasar light curve in the optical wavelength looks like a random noise - there seems to be no overall pattern underlying the changes in brightness. After power spectrum analysis it turns out that the signal is stochastic - close to chaotic, but with an inherent order. Stochastic variability can be characteristic of thermal processes, such as spread of instabilities in the disk - "hot spots", driven by the magnetohydrodynamic (MHD) processes (Kelly et al. 2007; Dexter & Agol 2011; Zu et al. 2013; Kozłowski et al. 2016). Therefore, parameters describing quasar variability on these medium-long timescales relate to the physical accretion parameters such as disk extent, its viscosity and temperature, strength of magnetic field. On shortest timescales of hours, only recently probed by Kepler, the light curves are also consistent with the MHD instabilities (Kasliwal et al. 2015; Aranzana et al. 2018; Smith et al. 2018). Recent reverberation mapping studies largely confirm this picture (Sun et al. 2015). One way of describing the variation in brightness over time is to plot the signal against time - that is the classic light curve. A light curve can be further characterized by a structure function (SF), that describes the root-mean-square scatter in magnitude differences between pairs of points as a function of time separation (Graham et al. 2014). SF tells us how much correlation there is between different parts of light curve, and it is also related to the power spectral density. SF can be seen as a mirror image of the Power Spectral Density (PSD), in a sense that while SF is a function of time differences, PSD is a function of frequency - time inverse. Processes that have a flat PSD - having an equal power across the entire frequency spectrum - are described as white noise, like white light that includes all colors. To further this analogy, stochastic processes that can be described by a simple power law, and yet depart from white noise, are termed "colored' noise, depending on the relative amplitude of PSD at various frequencies.

Thus we have red, pink, or blue noise (see Appendix C in Kasliwal et al. (2017)). Quasar light curves are consistent with Damped Random Walk model, or the PSD $\propto f^{-2}$, flattening at frequencies lower than that corresponding to the characteristic timescale τ (MacLeod et al. 2010; Zu et al. 2013).

1.5. *Quasar selection techniques*

Over the last decade new variability-based classification techniques have yielded detection of an unprecedented number of quasars allowing a population statistical study (Fan et al. 2001; Richards et al. 2006; Kozłowski et al. 2010; Palanque-Delabrouille et al. 2011; MacLeod et al. 2011; Graham et al. 2014; AlSayyad 2016; Ruan 2017). Classically quasars were selected using color cuts, which mainly targets quasars at redshifts around 0.5 <z <2.5 (Large Bright Quasar Survey, Hewett et al. (1995), the 2dF QSO Redshift Survey Croom et al. (2004), and the 2dF-SDSS LRG and QSO Survey Croom et al. (2009)). In addition to color space, SDSS I,II selected quasars via radio matches to the FIRST survey, or x-ray matches to ROSAT survey (Myers et al. 2015). Since then other classification methods have been tested, including radio source matching (McGreer et al. 2009), near-IR color cuts (Banerji et al. 2012), radio + near-IR (Glikman et al. 2012), mid-IR (Stern et al. 2005; Richards et al. 2009; Stern et al. 2012), X-rays (Trichas et al. 2012), midIR + X-rays (Lacy et al. 2004; Hickox et al. 2007, 2009), variability (Schmidt et al. 2010; Butler & Bloom 2011; MacLeod et al. 2011; Palanque-Delabrouille et al. 2011, 2016). There are some studies that combined color and variability information (Tie et al. 2017; Peters et al. 2015; Sesar et al. 2007).

1.6. *Variability with Damped Random Walk model*

A better understanding of how well the Damped Random Walk model can be used to model quasar variability is crucial for using DRW model best-fit parameters to characterize and classify quasars. It is a relatively recent field : Kelly et al. (2009) showed that DRW parameters can be linked to the physics of the accretion disk. Since Kozłowski et al. (2010) proposed the DRW model for quasar selection, MacLeod et al. (2010) moved the field of quasar variability studies from a handful of objects to a proper statistical study, fitting over 9 000 quasars in SDSS Stripe 82 with the DRW model Graham et al. (2017); Kozłowski, Szymon (2017) showed that when using the DRW model, the length of light curve is the most important predictor of biases for the best-fit parameters.

His main conclusion is that when the light curve length (baseline) is insufficient(less than 10 times the intrinsic timescale), then the bias will be larger than a few %. He showed that for a light curve of length similar to the intrinsic timescale, we expect the bias in retrieved timescale of a factor of 3, which we confirm in our independent study. We find with Celerite that a longer baseline can decrease the bias, which implies that the extended light curve can help improve the results of MacLeod et al. (2011).

Despite these advances, there are several crucial questions related to quasar variability that remain open. First, despite general agreement that the DRW is a good first-order description of quasar variability (Zu et al. (2011); Kozłowski et al. (2010)), there have been some inquiries to the fidelity of these descriptions on all timescales Zu et al. (2013); Kasliwal et al. (2017); Sartori et al. (2018). In particular, Graham et al. (2014) reported a detection of characteristic restframe timescale of 54 days, which has not been detected before. We aim to reconcile the CRTS data with the SDSS and PTF data for the same S82 quasars. It was surprising given that other studies more well tuned to short timescales did not report such findings (especially studies involving Kepler K2 AGN light curves with extremely good cadence - see Kasliwal et al. (2015); Aranzana et al. (2018); Smith et al. (2018)).

Second, although Kelly et al. (2011) showed that the DRW is a good description of the quasar variability, Kozłowski, Szymon (2017) suggested that with the method he employed there are biases in retrieved parameters. We want to evaluate the existing tools for fitting light curves (eg. the implementation of Rybicki & Press (1995) method, JAVELIN of Zu et al. (2011), George, Celerite, etc.), and find the best tool for future studies given their scalability (speed), memory usage, bias, to be prepared for fitting of billions of light curves in the LSST era.

Finally, we consider whether we can improve the "classical" method of light curve classification by using combination kernel Gaussian Processes. In the standard paradigm, to compare models A and B (eg. sinusoidal oscillation vs DRW), one needs to fit - optimize the cost function for model A and model B, calculate metric describing the 'goodness of fit' (eg. χ^2_{DOF}), and then choose a better fitting model based on that metric. We investigate a Bayesian method of fitting to the data a combination kernel Gaussian process, where one obtains simultaneously maximum a-posteriori estimates for amplitudes of component kernels.

2. PROPOSED RESEARCH

2.1. *Discrepant quasar timescales*

To answer the first question, we presented in Suberlak et al. (2017) an improved photometric error analysis for the 7 100 CRTS (Catalina Real-Time Transient Survey) optical light curves for quasars from the SDSS (Sloan Digital Sky Survey) Stripe 82 catalogue. The SDSS imaging survey has provided a time-resolved photometric data set, which greatly improved our understanding of the quasar optical continuum variability. Data for monthly and longer time-scales are consistent with a damped random walk (DRW). Newer data obtained by CRTS provided puzzling evidence for enhanced variability, compared to SDSS results, on monthly time-scales. Quantitatively, SDSS results predicted about 0.06 mag root-mean-square (rms) variability for monthly time-scales, while CRTS data showed about a factor of 2 larger rms, for spectroscopically confirmed SDSS quasars. Our analysis has successfully resolved this discrepancy as due to slightly underestimated photometric uncertainties from the

CRTS image processing pipelines. As a result, we found that the correction for observational noise was too small and the implied quasar variability was too large. The CRTS photometric error correction factors, derived from detailed analysis of non-variable SDSS standard stars that were re-observed by CRTS, are about 20−30%, and result in reconciling quasar variability behaviour implied by the CRTS data with earlier SDSS results. An additional analysis based on independent light curve data for the same objects obtained by the Palomar Transient Factory provides further supported for this conclusion. In summary, the quasar variability constraints on weekly and monthly time-scales from SDSS, CRTS and PTF surveys are mutually compatible, as well as consistent with DRW model, as described in Suberlak et al. (2017).

2.2. *Extending the light curve baseline, using the right tools*

We first confirm the scaling relations by Kozłowski, Szymon (2017) by testing the retrieval of simulated light curve parameters with Celerite . Using a similar MAP-based method we find with Celerite that the same bias in output light curve is found, and is primarily dependent on light curve length in relation to input time scale. Using a fixed light curve length of $t_{exp} = 8$ years we simulate 100 different input time scales τ_{in} , where $\rho = \tau_{in}/t_{exp} \in 0.01 : 15$. The bias is not affected by different cadence (we tested SDSS and CRTS cadences of N=80 or N=445 points).

Having established that extending the light curve baseline decreases the bias in retrieved DRW time scales we set out to improve on relations measured by MacLeod et al. (2011); Hernitschek et al. (2016) adding more data points to SDSS and PanSTARRS light curves (Chambers 2011). We do that by augmenting the existing light curves with additional data from PanSTARRS DR2 (Flewelling 2018) , CRTS (Drake et al. 2009), and PTF (Rau et al. 2009). We start from the SDSS DR7 near-simultaneous ugriz photometry for S82 quasars(Schneider et al. 2008). To use combined datasets we cross-match the catalogs, and find a common photometric solution using the S82 standard stars (PTF and CRTS use white light, Djorgovski et al. (2011)). Querying CRTS DR2 database B.Sesar obtained CRTS white light lightcurves for the S82 DR7 quasars. We obtained the PTF light curves from the PTF IRSA database. C. MacLeod provided the PS1 grizy light curves matched to positions from DR7 catalog. We validate data quality by comparing mean CRTS magnitude vs mean SDSS magnitude, and mean PS1 g-band to mean PS1 r-band.

We first simulate 10 000 DRW light curves at the SDSS cadence, and we test how adding more data (corresponding to PS1, PTF, CRTS datapoints) affects the fidelity of the retrieved to input parameters. Confirming that adding more data at these cadences improves the fit, we fit the real data with the DRW model, and using the spectroscopic information about the quasars (such as black hole mass, luminosity - Kelly et al. (2013)) we reconsider relations tested by MacLeod et al. (2011).

We also test how selecting photometry from only a subset of surveys τ_{PS1}, $\tau_{(PS1+SDSS)}$, τ_{SDSS}. We also revisit all relations using only bright quasars with $\tau_{\langle mag \rangle < 19}$.

2.3. *Improving the classical model fitting in the framework of Gaussian processes*

Classical model selection involves specifying a loss function that can be used to find best-fitting parameters for a given model. A suitable metric, such as χ^2, is used to describe the scatter of data around the model. Choosing a better model involves comparing the values of the loss function. A different approach is to simultaneously find the maximum a-posteriori solution for a model that combines the two. Such possibility is afforded by Gaussian Process with combination kernels, implemented in Célérité (Foreman-Mackey et al. 2017). For the last decade Gaussian Processes have become more well known, employing a class of functions that are characterized by covariance between pairs of points in the dataset (Foreman-Mackey et al. 2017). The combination kernel technique has been employed by Angus et al. (2018) to model quasi-periodic oscillation of star spots on top of the sinusoidally varying signal due to stellar rotation. Success of this approach furthers our interest in employing this methodology to mine the data for a sinusoidal signal superimposed on top of the DRW, such as is the case for the binary SMBH (Charisi et al. 2018).

We first test the combination kernel method, simulating a DRW light curve (parametrized by asymptotic amplitude SF_{∞}, and characteristic timescale τ) , with added sinusoidal modulation (parametrized by amplitude A, period P). With input characteristic timescale of $\tau = 100$ days, and regular sampling every dt = 5 days , we explore regimes from $A << SF_{\infty}$, to $A \approx SF_{\infty}$, and from $P << \tau$, to $P >> \tau$: $A \in \{0.01, 0.1, 0.25, 0.5, 0.75\} SF_{\infty} \times P \in \{0.25, 1, 4\}\tau$. We aim to find whether we can distinguish between a pure stochastic signal, and stochastic signal with sinusoidal modulation. We then test the combination kernel Gaussian process on spectroscopically confirmed SDSS S82 quasars, and finally find the combination kernel amplitudes for all SDSS S82 light curves.

3. TIMELINE

- Project "Discrepant quasar timescales"
  - published in Suberlak et al. (2017)
- Project "Improved constraints on quasar variability time scales"
  - Completed: identify an adequate fitting tool and confirm results about biased best-fit parameters from Kozlowski (2017)
  - Complete by May 15, 2018: collate the SDSS, Pan-STARRS, CRTS and PTF light curve data for ≈9,000 quasars from the SDSS Stripe 82 analyzed in the MacLeod et al. paper series
  - Complete by May 30, 2018: complete Célérité-based DRW fits

  - Complete by June 30, 2018: analyze results and produce a rough paper outline
  - Complete by Aug 31, 2018: produce the first draft of the paper
  - Complete by Sep 30, 2018: submit the second paper

- Project “Quasar/star light-curve based classification using Gaussian processes”
  - Complete by Dec 1, 2019: complete testing of the combination kernel method on simulated light curves
  - Complete by Jan 1, 2019: complete verification of the method on spectroscopically confirmed SDSS Stripe 82 quasars
  - Complete by Feb 1, 2019: complete combination kernel amplitudes for SDSS Stripe 82 objects
  - Complete by March 1, 2019: produce the first draft
  - Complete by Apr 1, 2019: submit the third paper

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