OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jul **Proposal type:** short-term

A Transformative Multi-Object AGN Reverberation Mapping Campaign: Continued Photometric Monitoring in 2015A

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Abstract of Scientific Justification

Accurately measured masses of supermassive black holes (BHs) are cornerstones for understanding the coevolution of active galactic nuclei (AGN) and massive galaxies. Mass estimates for distant BHs are tied to relationships derived from <50 AGN at $z < 0.3$ with masses measured from reverberation mapping (RM). We are pioneering a multi-object AGN RM campaign (SDSS-RM) on a uniform, magnitude-limited sample of 849 AGN with the SDSS-BOSS spectrograph. In RM, a virial mass is measured by properly combining an emission-line width with the distance of the line-emitting region from the BH, determined from the time lag between variations of an AGN's ultraviolet/optical continuum and variations of the emission line. Photometric monitoring is a critical component of successful RM: it produces precise continuum flux measurements, increases the spectrophotometric accuracy of the line fluxes, and provides more continuum/line cross-correlation points. The SDSS-RM program has finished successful 6-month baseline observations in 2014, and is being extended in 2015A-2016A to increase the temporal baseline. The extended SDSS-RM program will cover a more complete parameter space of AGN, detect a hundred more long lags (> 6 months) than possible in our 6-month baseline program, and enable a broad range of high-impact AGN science. We here propose a total of 15 epochs of two-colour Bok/90Prime photometry of the SDSS-RM field in 2015A to accompany continued SDSS spectroscopy.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	90”	PF	90Prime			15	bright/g	Jan–Jul	Jan–Jul	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*: Goal is photometric observations twice per month during bright time.

no text past this line

A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a ∗ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	SDSS-III RM field	14:14:49.0	+53:04:59	$\sim$ 850 spectrophotometric AGN targets

Approval for Instrument Use from PI: ______________________

(have instrument PI signature appear on, or attach PI e-mail to, ***all*** *copies)*

Graduate students *(provide the following information for* ***each*** *student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on* ***all*** *submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis

Scientific Justification

Scientific Background: There is longstanding interest in understanding the cosmic evolution of supermassive black holes (BHs) and their roles in galaxy formation and evolution. Believed to reside at the center of almost every massive galaxy with a significant bulge component, BHs can provide information about the accretion processes in the galaxy centers via Active Galactic Nuclei (AGN). They may also play important roles in the formation of the galaxy through feedback processes, as inferred from the observed tight local scaling relations between BH masses and bulge properties (Kormendy & Ho 2013). The mass of a BH (M_{BH}) encodes critical information about accretion processes during its active phase, and the mass evolution of BHs with cosmic time can depend on the processes behind the co-evolution between BHs and galaxies. Many current studies use M_{BH} values to estimate Eddington ratios and study accretion physics in AGN. Knowing the masses of BHs is thus of paramount importance to essentially all BH-related studies.

Measuring M_{BH} using resolved stellar or gas kinematics has been successful in several dozen local galaxies, but is primarily applicable to dormant BHs in nearby systems ($z < 0.1$). The only direct method to measure BH masses beyond $z = 0.1$ is reverberation mapping (RM, Blandford & McKee 1982, Peterson 1993) of broad-line AGNs. RM measures a characteristic broad line region (BLR) size from the time lag between variability of the continuum flux (which powers the BLR) and of the flux of a broad emission line. The time lag reflects the light travel time from the central BH to the region of the BLR with the strongest broad-line emission response. A virial M_{BH} can then be derived by combining the BLR size with the BLR gas velocity dispersion inferred from the broad emission-line width. Comparisons between RM masses and direct dynamical masses (in a few cases) or masses inferred from the $M_{\rm BH} - \sigma$ relation suggest that RM masses are accurate to within a factor of 3 (Shen 2013, Peterson 2013).

RM of nearby AGNs has revealed a remarkably tight correlation between the BLR size and the luminosity of the AGN, known as the "$R-L$" relation (Kaspi et al. 2005, Bentz et al. 2013). Subsequently this relation has been used to develop the so-called "single-epoch virial black hole mass estimators" (SE mass estimators hereafter): one estimates the BLR size from the measured AGN luminosity using the $R - L$ relation, and measures the width of the broad emission line, which are then combined to give an estimate of M_{BH} using calibration coefficients (Vestergaard & Peterson 2006) determined from the sample of AGNs with RM mass measurements (Peterson et al. 2004). This is currently the only practical way to estimate BH masses for large statistical AGN samples with SE spectra (e.g., 100,000 quasars in Shen et al. 2011).

The SDSS-RM Project - The first multi-object RM campaign

Yet there are significant concerns regarding these SE mass estimators, which are fundamentally limited by the current RM AGN sample. The only way to improve these SE mass estimators is by expanding substantially the sample of AGN with RM masses, to improve the statistics and cover AGN parameter space more uniformly. We are revolutionizing RM studies by performing the first-ever RM campaign using the SDSS-BOSS spectrograph (**SDSS-RM**; Shen et al. 2014). SDSS-RM targets a uniformly-selected AGN sample at $0.1 < z < 4.5$ down to $i = 21.7$ in a single 7 deg^2 field, offering considerably higher RM efficiency and free of pre-selection bias in AGN properties. Supporting photometric monitoring has been conducted with CFHT/MegaCam (dark/grey time) and the Steward Bok 2.3m telescope (bright time). We have finished a successful 6-month baseline program in 2014A, with 32 spectroscopic epochs and ~ 60 photometric epochs in g and i bands. The data are currently being processed and analyzed.

The SDSS-RM field coincides with one of the Pan-STARRS1 (PS1) Medium Deep fields that has been imaged in multi-bands in 2011–2013 with a cadence of several days. These early photometric data provide an opportunity to detect long lags (> 6 months) when combined with the spectroscopy from SDSS-RM. To maximize the potential of the PS1 early photometry, SDSS-RM will continue in the SDSS-IV/eBOSS survey (started in July 2014) to provide extended temporal baseline to facilitate the detections of long lags, with a reduced cadence compared to first-year observations. **This proposal seeks Bok/90Prime imaging in 2015A to accompany the continued spectroscopy.**

To demonstrate the improvement in the detection of long lags with continued monitoring over the baseline 6-month program, we simulate a two-year extension of the SDSS-RM program starting from 2015A. With a two-year extension in 2015-2016, we will be able to double the detections of long lags, and improve the fidelity of these detections substantially. This would provide an unprecedented sample of quasars with RM measurements, and groundbreaking insights on quasar physics, the growth of supermassive black holes, as well as the coevolution of BHs and host galaxies.

Our campaign will mitigate the following limitations in existing RM data: **(1)** only $\lesssim$50 AGNs have RM data to date, a sample almost exclusively at $z < 0.3$ which poorly probes the high-luminosity AGN population; **(2)** the RM AGN sample does not probe broad-line AGN parameter space uniformly (lacking objects with relatively narrow BLR lines and strong Fe II emission, e.g., Shen 2013), and is highly biased relative to typical high-redshift quasar emission-line properties (lacking objects with large C IV blueshifts and small equivalent widths, e.g., Richards et al. 2011); **(3)** the $R - L$ relation has only been established for Hβ, as RM data on local AGNs are insufficient to derive an $R - L$ relation for C IV and there are little data on Mg II; **(4)** nevertheless, Hβ, Mg II, and C IV are all being used as SE mass estimators for high-z quasars. All these issues result in substantial uncertainty and potential systematic biases, ~ 0.5 dex, of these SE mass estimators relative to RM masses (Shen 2013; Peterson 2013), a situation which desperately needs improvement.

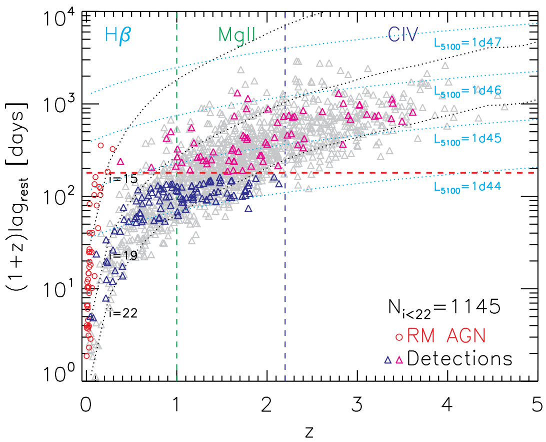
The Need for Photometry: Well-sampled, high-S/N photometric light curves are a critical component of any RM program (e.g., Denney et al. 2009): **(1)** they remedy weather losses in spectroscopic continuum measurements; **(2)** more accurate photometric continuum measurements reduce uncertainties in the continuum/emission-line lag measurements; **(3)** the more frequent continuum sampling also leads to higher precision lags and less aliasing between multiple variability events; **(4)** near-simultaneous photometry improves the spectrophotometric accuracy of the SDSS observations, reducing our line flux error budget: **(5)** independent photometry reduces correlated errors in the continuum- and line-flux measurements from spectroscopy alone.

Science Impact: SDSS-RM will yield the following advances, as summarized in Shen et al. (2014).

• Reliable direct BH mass measurements based on RM for AGN up to $z \sim 3$. This will have tremendous influence on studies of the co-evolution of BHs and host galaxies. Thus far all studies of the evolution of the BH-bulge scaling relations rely on BH mass estimates from SE methods, which suffer significant statistical and systematic uncertainties and biases (Shen 2013 and references therein). The compilation of a large sample of AGN over a wide redshift range with much more reliable RM masses will revolutionize such studies.

• Better calibrations of the BLR size-luminosity relations not only for Hβ, for which we will have better statistics and more uniform sampling of quasar properties, but for the first time for Mg II and C IV as well. These improved and new calibrations will be the foundation for developing better SE mass estimators and for critically evaluating the feasibility of using the $R - L$ relations as a luminosity indicator for cosmology (e.g., Watson et al. 2011).

• Better understanding of BLR structure and improved general RM techniques: **(1)** simultaneous RM for multiple broad lines in the same object (e.g., Lyα, C IV, He II, C III], Mg II, Hβ), important to test the assumption that the BLR clouds are gravitationally bound to the BH and to measure the BLR stratification by comparing BLR size as a function of ionization; **(2)** new algorithms for lag measurements (Zu et al. 2011) and for constructing velocity-delay maps (Grier et al. 2013); **(3)** composite RM, which can provide statistical lag detections even when individual detections are impossible (Fine et al. 2013), useful to expand the range of the $R - L$ relations.



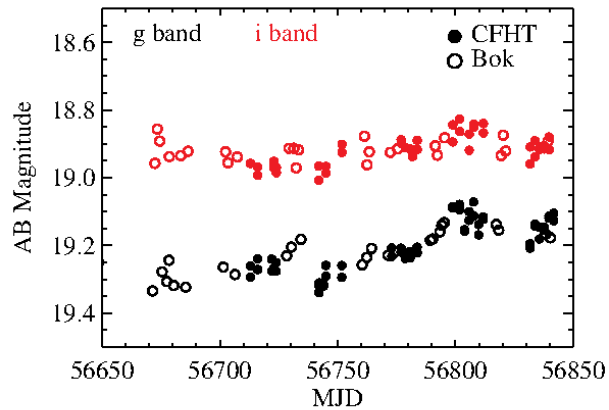


Figure 1: **Left:** Gray points are the quasars on a single SDSS plate ($\sim 7\,\mathrm{deg}^2$) from our target field. The vertical axis is the expected lag in the observed frame, determined by the BLR size from the $R-L$ relation in Bentz et al. (2013) with 40% scatter. The red horizontal line indicates the length of the approved SDSS program. Simulated detections are shown in blue for the baseline program in 2014A. **By extending the program to 2015A, time lags for objects at higher luminosity and redshift can be obtained** (magenta points), considering Hβ RM for $z<1$, Mg II RM for $1<z<2.2$ and C IV RM for $z>2.2$. The current RM AGN sample is shown using red circles. Black dotted lines show the approximate correspondences to different (dereddened) i-band magnitudes, while the blue dotted lines show those for constant 5100 Å continuum luminosities. **Right:** Light curve of an individual RM quasar from 2014A, combining the Bok and CFHT photometry. Continuum variation features are clearly visible in the roughly two-day, continuous cadence. For 2015A, we will again employ Bok and CFHT, but now a longer cadence (∼weekly) in order to recover longer time lags.

References

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Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

Our RM field is the PS-1 MD07 field (213.704+53.083) in CFHTLS W3. This field has: **(1)** maximum A semester visibility; **(2)** 849 spectroscopically confirmed quasars to $i = 21.7$; **(3)** 2011A-2013A photometry from the PS1 Medium Deep survey (now suspended), which will be combined with our spectroscopy to detect $>$ 6-month lags in high-z AGN. The SDSS-RM baseline program has finished taking data in 2014A, with 32 spectroscopic epochs and $\sim$ 60 photometric epochs (g+i) from CFHT and Bok. SDSS-RM will continue monitoring the RM field spectroscopically in 2015-2016 with a monthly cadence in order to detect long ($>$ 6 months) broad-line lags of luminous quasars. Our requested photometry has two primary purposes:

(1) Provide independent, well-sampled photometric light curves (i.e., AGN continuum monitoring) to cross-correlate with spectroscopic line flux light curves. The typical AGN continuum and broad line variability on the timescales of our experiment are at the $\sim 10\%$ level; thus, precision photometry at the $\lesssim$4% level enables the tracing of continuum variations with enough fidelity to yield a detectable signal when cross-correlated with the line-flux measurements. The addition of regular, independent photometric monitoring will increase our lag detection rate.

(2) Provide instances of photometry on nights not far (i.e., within a week) from spectroscopy for improved spectrophotometry of the latter (for the luminous quasars of interest to the extended SDSS-RM program, the variability over days intervals is negligible). The SDSS-BOSS pipeline spectrophotometry is at the 6% level. Photometry to $\lesssim$ 4% can improve the spectrophotometric calibration to similar precision.

Since the primary purpose of continued monitoring of the SDSS-RM sample is to detect long lags, we require a much reduced cadence in spectroscopic and photometric monitoring. The spectroscopic cadence will be once a month. We therefore require photometric monitoring once every week to have a well-sampled photometric light curves, with two epochs in each dark run from CFHT, and two epochs in bright time from Bok.

Filters and Exposure Time: We require 2 filters (g and i) to cover both low-z and high-z quasar continua. These two filters optimize the efficiency of the imaging observations given the need for different bandpasses. We need 9 pointings with 90Prime in each filter to cover fully the 7 deg^2 RM field (each divided into two dithered exposures to cover chip gaps). We require a point-source SNR=25 at $i = 22$ (our sample limit) and SNR=25 at $g = 22.25$ ($\langle g - i \rangle = 0.25$ for $z < 2.2$ AGN). We require 4% photometry to improve significantly the quality of the lag detections. Our experience from 2014A shows that these goals can be achieved in 4-6 hours per epoch.

Scheduling: We recognize that the Bok telescope may have a substantial amount of observing time set aside for a large survey in 2015A. The RM program would integrate well with that program. First, RM observations could be conducted while the Moon is up during grey time, potentially filling gaps in the schedule. Secondly, RM observations can be scheduled adjacent to the 90Prime survey, without necessitating an instrument/secondary change.

As a final note on scheduling, because CFHT would not commence observations until February, **we request 4 epochs of Bok-RM observations in January**. In July, only one epoch is possible before shutdown. For all other months, we request 2 epochs. This brings the total number of epochs to 15. We need the equivalent of one night to cover both the g and i bands, with sharing of the nights strongly preferred due to field visibility.

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

This program was allocated $\sim$40 nights with 90Prime on the Bok telescope in 2014A, and 100 hours with CFHT Megacam, in addition to 30 spectroscopic epochs with the SDSS telescope. The Bok data provide over half of the photometric coverage during 2014 and will be instrumental in the final analysis.

The technical summary of RM has been published (Shen et al. 2014). Multiple papers are in preparation while the data is being analyzed, including a summary of the photometric observations, structure functions of various emission lines, spectral decomposition of host/AGN components, quasar photometric variability, etc.

We are also requesting UKIRT time to monitor the RM field, for a separate (but related) program to do dust reverberation mapping in the near-infrared.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). (**up to one page**)*

LaTeX 2$_\varepsilon$ UAO Observing Proposal class, 'soprop.cls' v1.3 (2007 Aug 01 [RAJ]).