OBSERVING REQUEST
University of Arizona Observatories

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

A Transformative Multi-Object Reverberation Mapping Campaign: Dust Geometry from UKIRT Observations

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Abstract of Scientific Justification

We have conducted the first multi-object reverberation mapping campaign with a sample of 850 quasars in a single 7 deg^2 field. This program combined 30 epochs of SDSS spectroscopy and $>$100 epochs of Bok and CFHT photometry in 2014A, and is being extended to 2015-2016 with continued optical photometric and spectroscopic monitoring. The primary goal of the optical RM campaign is to obtain robust black hole mass measurements for a large sample of quasars using the time delays between the continuum variations and the emission lines in the broad-line region. A similar method can be applied in the near-infrared in order to measure time delays to the dusty torus thought to surround the nuclear region, at scales roughly a factor of ten greater than the BLR. Building on our 2014A observations, monitoring of the RM field with UKIRT/WFCAM in 2015A and beyond will allow measurements of dust time lags for several tens of quasars out to $z \sim 1$. This would dwarf current samples in terms of the number of objects and the luminosity and redshift ranges covered by our study, and provide meaningful statistics on the distribution of dust torus radii. The existence of a luminosity-radius correlation for dust (with a physical origin from the luminosity-dependent dust sublimation radius) may provide a powerful tool for obtaining cosmological constraints, a possibility our sample is uniquely suited to study in detail. Finally, by coadding multi-epoch K-band photometry (we propose for eight epochs at $\sim$ 4 hours per epoch in 2015A) of the RM field we can detect the quasar host galaxies and obtain reliable stellar mass estimates, allowing the quasars to be compared to bulge-black hole relations.

Summary of observing runs requested for this project

								Scheduling		Sharing	
Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Optimal	Acceptable	Poss.	Adv.
1	UKIRT		WFCAM			3	bright	Jan–Jul	Jan–Jul	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)*: We desire a $\sim$20 day cadence for individual observations as part of a monitoring program.

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-RM Field	14:14:49.00	+53:05:00.0	850 quasars with $i < 21.7$

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

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

Reverberation mapping (RM) is a powerful technique for characterizing the geometry of the nuclear region of quasars using time-domain data. Optical RM consists of monitoring quasars spectroscopically, in order to resolve the time lag between ultraviolet fluctuations arising in the inner accretion disk, and their delayed response in the broad-line region (BLR). This delay depends on the radius to the BLR, and under asssumptions about the geometry and kinematics of the BLR clouds, can be used to obtain virial black hole mass estimates.

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 $\sim$ 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.

The RM project has the primary goal of detecting time lags between continuum variability arising from the accretion disk and its emission-line response in the broad-line region (BLR) through continuous optical monitoring (photometric and spectroscopic). The expected lags are of order tens of days in the rest-frame. In unified models, AGN have a dusty torus residing outside the BLR. This torus is heated by the UV continuum photons and similarly responds to continuum variations. The scale of the dust torus is about a factor of ten greater than that of the BLR, thus the rest-frame time lags are of order hundreds of days. Currently ~ 40 AGN have optical RM measurements, while only a handful have been monitored at infrared wavelengths to measure the dust response times. **There are 81 quasars in the RM target sample with $z < 1$ and $i < 20$ that are the most promising targets for dust RM detections.** The redshift distribution of the full sample peaks at $z = 1.5$ and extends to $z = 4$; the higher redshift quasars will have weaker dust signals in the K-band but provide a compelling sample for studies of quasar color variability by tying in the g and i band time-series photometry. The K-band data will also provide an important probe of the quasar host galaxies.

While the RM field is rapidly accruing optical data, it is poorly covered at other wavelengths, *with no near-IR coverage beyond 2MASS*. We propose long-term (at least two years) near-IR monitoring of this field with UKIRT with the following goals:

Geometry of the dust torus: Although the scale of the dusty torus is much greater than that of the BLR, it is nonetheless far too small to spatially resolve except for the most nearby objects. This program would yield the first detections of dust reverberation mapping time lags for potentially tens of objects simultaneously, using homogeneous and well-sampled data, vastly exceeding work published to date. A large sample of quasars with dust RM time lags would provide statistics on the radius of the dusty torus, its covering factor, and how this geometry relates to luminosity or other AGN characteristics.

Deep K-band imaging of quasar host galaxies: Coaddition of the optical and near-IR imaging to build deep object catalogs over a large area, enabling accurate photo-zs and studies of the AGN and galaxy luminosity functions, clustering, etc. In addition, many objects in the RM sample are at low redshift and have host galaxy detections in the optical; corresponding K-band data will provide (after subtraction of the central point source) strong constraints on the stellar mass of the host galaxies and allow them to be placed on BH-bulge relations, *using the accurate, RM-based BH mass estimates combined with K-band stellar masses.*

Near-IR monitoring: A long-term buildup of near-IR photometry to complement the impressive optical photometry in this field. The RM collaboration is exploring options to extend the program over several years in order to detect longer BLR time lags from higher redshift quasars. Simultaneous near-IR monitoring over the same time period would be a first on this scale and allow probes of variable and transient phenomena in both the optical and near-IR.

Cosmological implications - quasars as standard candles: Given that they are visible to great distances, quasars have long been sought after as cosmological probes, if there were some means to use them as standard candles. The dust sublimation radius sets the innermost region where the dusty torus can extend, and this radius is set by the AGN luminosity. Indeed, previous work has shown that the sublimation radius scales as the square root of the AGN luminosity (e.g., Suganuma et al. 2006). Using this relation between luminosity and distance, where the distance is obtained from RM time lags, provides a measurement of the luminosity distance independent of redshift, and thus a standard candle (Hönig 2014, Yoshii et al. 2014). This method has only been applied to a handful of nearby objects (< 20 at $z < 0.1$), by greatly expanding the sample of quasars with dust time lags this method can be examined with better statistics, and potentially provide new distance measurements out to $z \sim 1$. If this method can be well established, it could provide a powerful tool for obtaining distances at very high redshifts.

References

[1] Hönig, S. F. 2014, ApJ , 784, L4

[2] Shen, Y., Brandt, W. N., Dawson, K. S., et al. 2014, arXiv:1408.5970

[3] Suganuma, M., Yoshii, Y., Kobayashi, Y., et al. 2006, ApJ , 639, 46

[4] Yoshii, Y., Kobayashi, Y., Minezaki, T., Koshida, S., & Peterson, B. A. 2014, ApJ , 784, L11

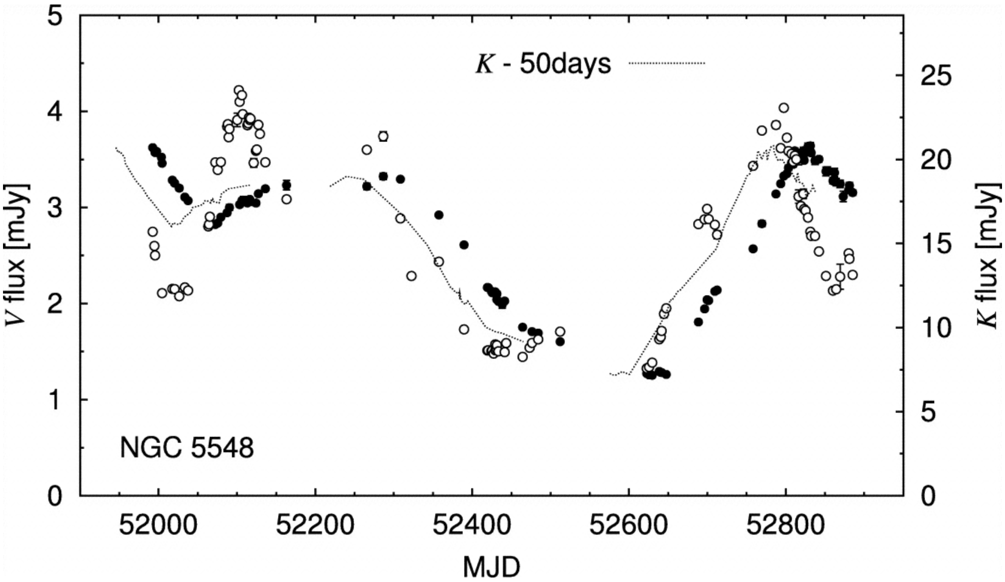

Figure 1: Fig. 14 from Suganuma et al. 2006, showing the V (open circles) and K (filled circles) band lightcurves of NGC 5548. The K-band light curve is then shifted by 50 days (gray line) to demonstrate the time lag from the V band fluctuations.

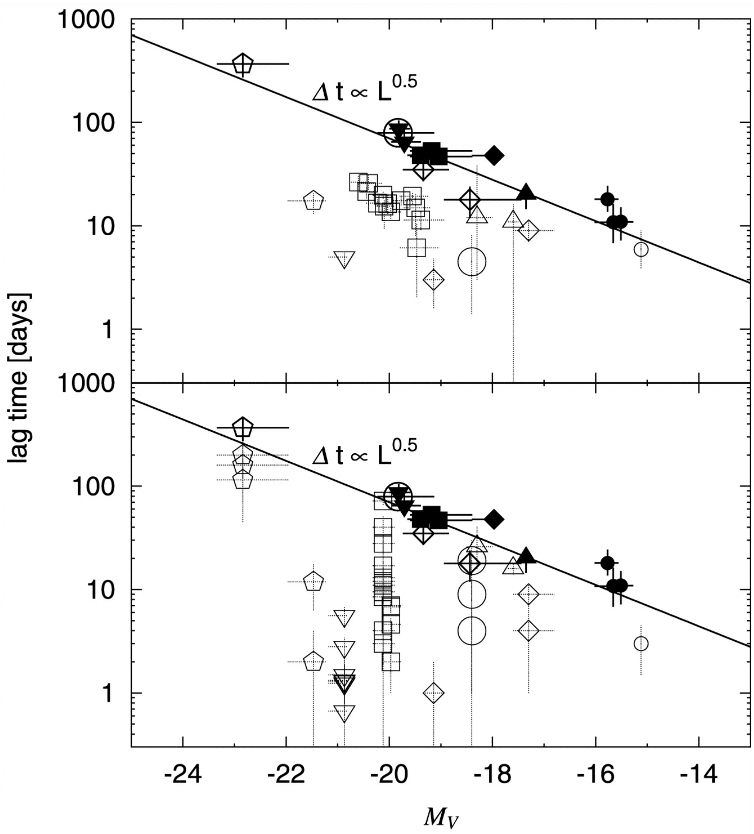

Figure 2: Fig. 32 from Suganuma et al. 2006, showing the infrared luminosity-time lag relation for nearby AGN. The RM sample sits at the high-luminosity end of this plot, with predicted rest-frame time lags of 1-3 years.

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)***

The field location is **14h +54d**. Covering the field with WFCAM requires ~ 40 individual pointings. Individual 6m exposures will reach a depth of $K_{\rm AB} \approx 21.5$ (5σ), requiring ~ 4 hours to cover the field. This is deep enough for variability measurements with 10% photometry for the majority of the RM quasars (matched to $g = 21$). A cadence of ~ 20 days is desired to sample the lightcurve at $\sim 1/10$ of the expected time lag (Figure 2).

Accumulating total of 8 epochs in the K band would approach the limiting optical mags of MD07 ($K \approx 22.5$) when coadded. It would also provide baseline for continued monitoring to detect long time lags in future years. This results in a total request of 36 hours (including 0.5hr overheard per epoch).

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.

We intend to propose for additional Bok and CFHT optical monitoring in 2015A, at a cadence of 2 epochs per month each. In addition, there are plans to continue the spectroscopic monitoring in SDSS-IV.

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**)*

⋆ *A Transformative Multi-Object AGN Reverberation Mapping Campaign: Photometric Component* (2014A) – A large campaign to provide photometric data to complement multi-epoch spectroscopy with the SDSS telescope for the purposes of Over 60 epochs of g+i imaging obtained. First version of reduction pipeline has been released to the collaboration. Technical paper submitted, two more papers in preparation.

An LSST Pilot Survey: High redshift quasars from multiple-epoch imaging and the $z \sim 4$ *luminosity function* (2013B,2014B) – Four nights in 2013B; three telescope did not open, first night observed backup targets in poor conditions. Three nights in 2014B scheduled.

Physical properties of the brightest Lyα-emitting galaxy at $z > 5$ *from deep optical spectroscopy* (2013A/2014A) – One night in 2013B with LBT/MODS. Much of the run was lost to bad weather. Obtained two hours of observations with one mask. 1.5 nights in 2014B. No additional spectroscopy obtained due to weather. Obtained 0.5 hrs g-band imaging and some poor K-band imaging. Discovery paper is in preparation.

⋆ *varBoötes: A Study of AGN Variability in the NDWFS Boötes Region* (2012B/2013A/2014A) – Several epochs of imaging on Boötes obtained. Data quality is very good for most epochs. Some data is reduced and we have checked that the S/N at the faint limit is sufficiently high for variability studies. Project is now being folded into tests of target selection in SDSS-IV/eBOSS as well as quasar variability studies with the SDSS-III Reverberation Mapping campaign.

The Faint QSO Luminosity Function at $z \sim 5$ *From CFHTLS-W3* (2012BC/2014A) – Four nights in 2012 resulted in ~ 20 new quasars in the CFHT fields. One night in 2014 lost to weather. MMT data will be combined with two nights of Gemini data to provide the first measurement of the $z \sim 5$ QLF to $i \sim 24$. One paper published (from 2011 data on similar program), analysis for second paper started.