A Feasibility Study of Photometric Reverberation Mapping using Meter-Class Telescopes

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Abstract

We analyzed the feasibility of an observational program to efficiently and accurately estimate masses of central supermassive black holes hosted by Active Galactic Nuclei (AGN). For the past 40 years, this has been accomplished using Reverberation Mapping (RM), which generally entails months of observations of simultaneous photometric and spectroscopic data and large-telescope time, which must be proposed sometimes years in advance. Due to this barrier, less than 50 AGN have had RM applied. Our method modifies RM for moderately-sized telescopes, e.g. 0.9-m hosted by West Mountain Observatory. We present a feasibility study of our photometric RM method with the AGN NGC 5548. We found a black holes mass estimate $M_{\rm BH} = 67.2 \pm 2.2 \times 10^6 M_\odot$ (with $f = 5.5$) and a lag of $\tau \approx 3.3$ days.

1 INTRODUCTION AND BACKGROUND

An active galaxy is one that has an energy source in the central portion of the galaxy with radiation that cannot be attributed to stars. This central structure is known as an AGN and is pictured in Fig. 1. The radiation results primarily from material falling onto the accretion disk, very close to the central black hole. This light is radiated in all directions. Some of this light is directed into the broad-line region, a few lightdays or lightweeks from the center of the AGN (see Fig. 2). Just as one can hear an echo after sound bounces off a wall, the gas in the broad-line region can absorb some of the light emitted near the accretion disk and reemit. This "echo" of light will be easily distinguished from the original, central emission because the reemitted light will radiate at wavelengths that encode the signature of the material in the broad-line region. A distant observer will see a time lag on the order of a few days between the original central emission and broad-line reemission. This time lag provides information about the broad-line region, which is crucial to estimating the mass of the central, supermassive black hole. Utilizing this echo effect of light is the basis for the central mass estimate through a technique called reverberation mapping.

The measurement of the reemitted light maps out a specific region and thus will not be a single unique measurement. The broad-line region contains broader emission lines due to the fast moving material within the region. This is generally between a few lightdays and a few lightweeks in radius, making the structure fairly compact. This measurement will vary due to different velocity dispersions for the different Doppler broadened lines that arise at various distances. The broad-

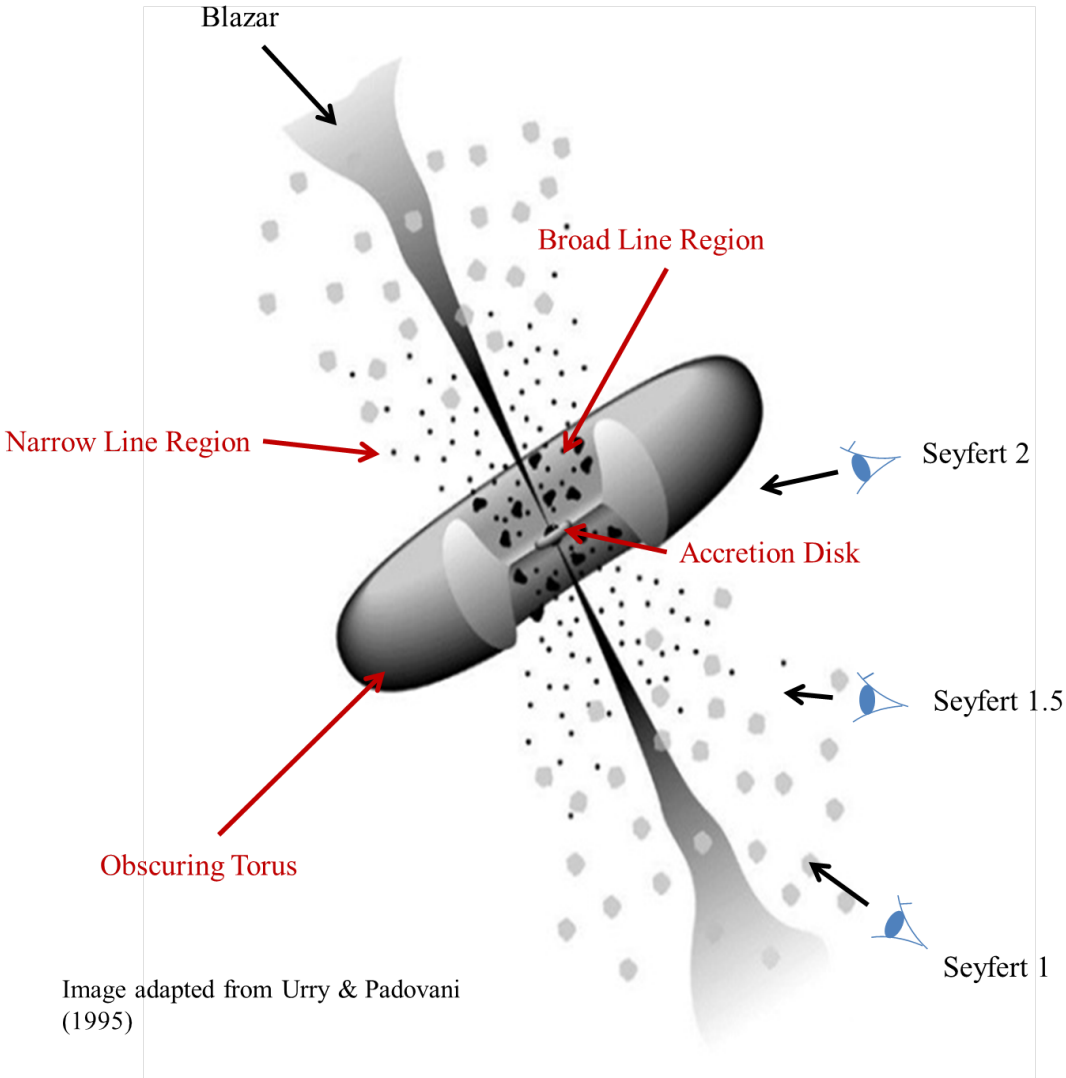

Figure 1: Active Galactic Nuclei (AGN) Unification Model: The Unification Model combines the different types of AGN into one explanation based on viewing angle. This model shows the black hole at the center with a nearby accretion disk of fast moving matter. Near the accretion disk is the broad-line region. Image adapted from [23].

ening should be slightly larger for the higher energy lines that are closer to the central mass.

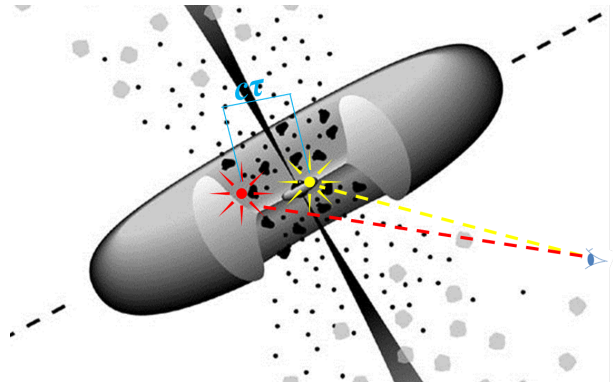

Figure 2: Light radiates first from the central portion of the AGN in all directions (in yellow). After a few days/weeks of travel, some of the photons will interact with material in the broad-line region (see Fig. 1), which will absorb, then reemit the light (in red). Radiation from the two sources will be seen with a time lag, which gives the broad-line region radius ($c\tau$). This is like sound bouncing off of a wall and delivering an echo.

Further out from the center of the AGN, lower energy gas will be present. Emission features in IR will be further from the black hole than Hα emission [12]. Thus, a broad-line radius measurement will be specific to the emission. Though observing different elements will yield various radii for the broad-line region, all will be within a close enough region that from this point on, the broad-line region will refer to only one value, using Hα measurements exclusively.

The reveberation mapping technique [20] assumes the standard model sketched in Fig. 1. It also assumes that AGN follow the same relationship between black hole mass and host-galaxy bulge velocity dispersion [15] as observerd for non-active galaxies. Variability measurements yield the aforementioned time lag and thus the radius of the broad-line region. We assume the system is virialized, or that $-2K = U$ [5], where U is the gravitational potential energy of the gas clouds in the broad-line region, $U = -G\frac{M_{BH}m}{r_{BLR}}$ and K is the kinetic energy, $K = \frac{1}{2}m\Delta v^2$, where Δv is the velocity dispersion within the broad-line region. This yields a virial mass estimate,

$$M_{BH} = f\frac{\Delta v^2 c\tau}{G},$$

where f is a scaling factor, Δv is the Doppler broadening velocity, $c\tau$ is the radius of the broad-line region, and G is the gravitational constant.

The current methodology for reverberation mapping of AGN requires the use of simultaneous and continuous spectroscopic and photometric data. This demands the use of telescopes of at least two meters. Since large-scale reverberation mapping projects have been fairly inaccessible to small research groups, less than 50 AGN have been reverberation mapped. Large telescope time is difficult to acquire and can even be wasted in the event that the short time allotted occurs during bad weather or at a time when the target object is in a quiescent state. However, a modified version of the traditional reverberation mapping technique that requires minimal spectroscopic information eliminates the need for large telescope time and would make these projects possible at observatories with more moderately sized telescopes, such as Brigham Young University's West Mountain Observatory hosting a 0.9-m Cassegrain telescope.

2 PROBLEM AND OBJECTIVES

We propose an observational program designed to estimate the masses of black holes near the center of Seyfert 1−1.5 AGN in order to evaluate a modified reverberation mapping technique that relies on photometric observations that can be secured with 1-meter class telescopes. Similar methods to that proposed in this project have been utilized in the last few years and have shown to yield

useful results [6, 7, 11]. We modified previous techniques to create a multiband photometric reverberation mapping method that can be applied using modest equipment that is available at many small observatories.

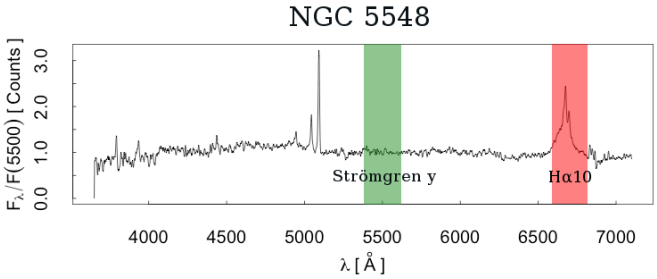

Figure 3: Archival spectra of NGC 5548 from the NASA/IPAC Extragalactic Database (NED) superimposed with the broadband Strömgren y-filter and narrowband filter Hα_{10} (see Tables 1 and 2).

3 METHODOLOGY AND PROCEDURES

The general method to obtaining black hole masses through photometric reveberation mapping requires a filter capturing the desired emission feature as well as a filter capturing the contiuum (example shown in Fig. 3). In 2012, we used a broadband filter set (Table 1) to observe one AGN, Mrk 926 (see Table 3). During the three months of data acquisition, we found Mrk 926 relatively quiescent and were unable to provide a black hole mass estimate. In 2013, we observed five additional AGN (KIC11178007, Mrk 50, Mrk 817, Mrk 926, NGC 4051, Zw299-015 as in Table 3) using the aforementioned broadband filter set and an additional set of narrowband filters (Table 1). The analysis of this data is currently in progress. Preliminary results of this analysis indicate significant variability allowing for potentially possible time lag extraction.

In comparison to traditional reverberation mapping, the photometric technique requires only archival reference spectra to estimate the velocity dispersion from the Doppler-broadened lines that arise in the broad line region of the AGN. Most AGN are faint enough that, in order to monitor the changes in flux from the broad-line reverberation, it is necessary to secure spectra and integrate the flux in the broad lines semi-continuously over periods of several months (depending on the size of the lag time). Spectroscopic observations require much larger telescopes compared to photometric observations on the same objects. We note that the position of the relative broad-line region will vary slightly in time due to the level of outburst that is coming out of the nucleus. However, this is a secondary effect and should not impact an estimate derived with a photometric technique and a single epoch spectrum. In 2014, we observed data from NGC 5548 between January 25 and August 29 in four filters: Hα_{10}, Strömgren y, Johnson/Cousins V and Johnson/Cousins R (see Tables 1 and 2).

The cross-correlation function finds the difference between two similar signals, or light curves, from the continuum measurement and the emission feature measurement. The curves are similar but not identical, and we expected to see a time lag of a few days for corresponding increases in brightness between the light curves. In observations highlighting the emission feature, the signal or light curve showing the variability is a convolution of light from the continuum measurement and the variability from the emission feature.

4 RESULTS

Using JAVELIN, the cross-correlation python-based program written for reverberation mapping [27, 25, 26], we estimated time lags for NGC 5548 between the H$a\alpha_{10}$ filter and 3 continuum filters: Strömgren y, Johnson/Cousins V and Johnson/Cousins R. JAVELIN produced a time lag of

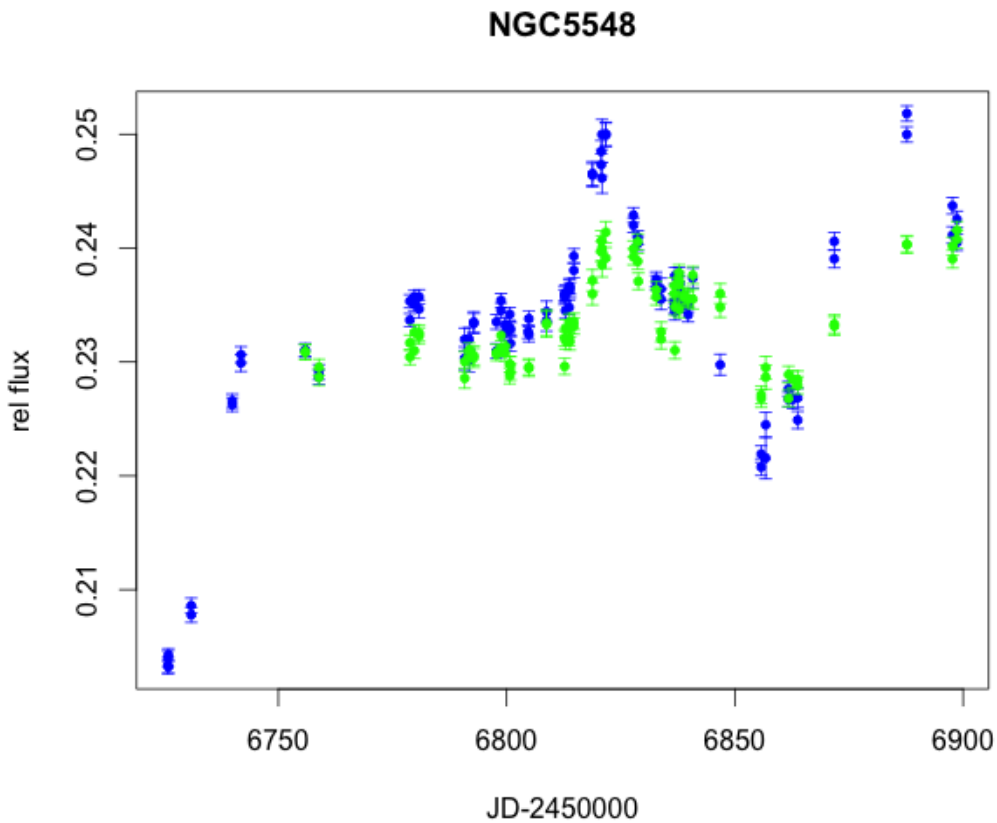

Figure 4: NGC 5548 Light Curve Comparison between Strömgren y (shown in blue) and Hα_{10} (shown in green). This plot shows relative flux on the y-axis and in both plots the Hα_{10} flux data was shifted by a small amount to enable data from all filters to align along the y-axis.

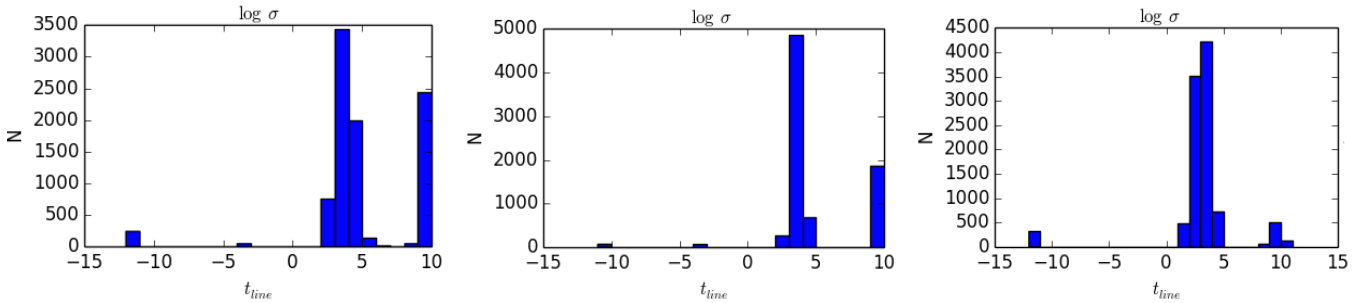

Figure 5: Left image: JAVELIN analysis comparing Strömgren y band with Hα_{10}. With a lag limit set to $\pm$20 days, this produced a lag of 3.2 days. Center image: JAVELIN analysis comparing Johnson/Cousins V band with Hα_{10}. With a lag limit set to $\pm$20 days, this produced a lag of 3.3 days. Right image: JAVELIN analysis comparing Johnson/Cousins R band with Hα_{10}. With a lag limit set to $\pm$20 days, this produced a lag of 3.4 days.

$\tau_y = 3.3 \pm 0.1$ days comparing the Strömgren y to the Hα_{10}, $\tau_V = 3.4 \pm 0.3$ days comparing Johnson/Cousins V to the Hα_{10} and $\tau_R = 3.4 \pm 0.2$ days comparing Johnson/Cousins R to the Hα_{10} (see Fig. 5 for one example). Given that b2009 found a time lag of 4.25 days between an Hβ emission and the Johnson/Cousins V filter, these results are reasonable.

With such a variety of options available for Δv and f, many options exist for a black hole estimate even with only one time lag τ. Using the time lag from the Strömgren y and Hα_{10} filters and a velocity dispersion of 4354 ± 25 km/s [18], we estimate the black hole mass estimate to be $M_{\rm BH} = 67.2 \pm 2.2 \times 10^6 M_\odot$. As the value of $f = 5.5$ is the most commonly accepted value for f presented in modern literature [4, 9, 17], we chose to use this value as our main SMBH mass to report.

5 SIGNIFICANCE OF THE RESEARCH

Most if not all galactic nuclei contain supermassive black holes with $M > 10^6 M_\odot$. Whether these black holes originate through supernovae, collisions, mergers or other processes, it is generally accepted that each galaxy likely hosts a supermassive black hole in its nucleus. Because these nuclei are embedded in dense star fields, we know little about the details and structure of the regions surrounding them. Without this knowledge it is difficult to know anything about their formation and evolution.

Mass is one key link to this information and the most measurable characteristic of black holes. Mass estimates of black holes would provide greater empirical data to fit models of mass distribution throughout the universe and would bring insights into the foundations of quantum-gravity theories [6].

Also, a photometric reverberation mapping technique performed on meter-class telescopes would enable supermassive black hole mass estimates to be made by any group with the right filter set and meter-class telescopes. Such equipment is relatively common among universities and would significantly increase the supermassive black hole mass estimates. Considering the small sample size of supermassive black hole mass estimates from reverberation mapping, this project would allow small research groups everywhere to apply this method. As there are thousands of AGN that may qualify for this photometric reverberation mapping method, we expect the number of estimates to increase from approximately 40 to several hundred within a few years of application. More estimates would yield greater accuracy to theories on mass distribution throughout the universe, formation of supermassive black holes, galactic evolution, and dark matter.

We expect continuations of this project will enable many other small facility astronomers to apply photometric reverberation mapping to many more AGN than before. This will provide additional insights into the environment close to the black holes near the center of AGN.

6 ACKNOWLEDGEMENTS

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Table 1: Filters currently available at WMO. The Johnson/Cousins broadband filter set and the Strömgren intermediate-band filters were primarily used for continuum measurements according to the best fit for each AGN. The narrowband filter sets ($\Delta\lambda \leq 5$ nm) and the selected intermediate bands listed highlight the Hα and Hβ emission features.

Name	λ_{eff}	$\Delta\lambda$	Name	λ_{eff}	$\Delta\lambda$
Sloan			Strömgren		
u'	352 nm	65 nm	u	350 nm	30 nm
g'	475 nm	150 nm	v	410 nm	16 nm
r'	630 nm	133 nm	b	470 nm	19 nm
i'	795 nm	149 nm	y	550 nm	24 nm
z'	873 nm	94 nm	Hβ		
Johnson/Cousins			WB	486 nm	15 nm
B	445 nm	94 nm	NB	486 nm	3 nm
V	551 nm	88 nm	Hα		
R	658 nm	138 nm	WA	656 nm	20 nm
I	806 nm	149 nm	NA	656 nm	3 nm

Table 2: Filters installed for use at West Mountain Observatory after April 2014. Maximized results for each object are obtained with filters that are centered on Hα at the redshift of the object.

Filter	λ_{eff}	$\Delta\lambda$	Redshift Range
Hα_{00}	656.3 nm	20 nm	$0 < z < 0.009$
Hα_{10}	667 nm	21 nm	$0.009 < z < 0.024$
Hα_{20}	677 nm	21 nm	$0.024 < z < 0.039$
Hα_{30}	687 nm	21 nm	$0.039 < z < 0.054$
Hα_{40}	697 nm	21 nm	$0.054 < z < 0.070$
Hα_{50}	707 nm	21 nm	$0.070 < z < 0.085$
Hα_{60}	717 nm	21 nm	$0.085 < z < 0.100$

Table 3: Original AGN targets sorted by right ascension. In the original Ph.D. project, we planned to obtain black hole mass estimates for at least four AGN and perhaps for all the AGN listed. In the revised M.S. project, we chose to focus on NGC 5548 as it is likely the best studied AGN by reverberation mapping [22] and was the subject of recent in-depth analysis by the Space Telescope and Optical Reverberation Mapping (STORM) Project [10].

Name	RA	Dec	z
UGC 3374	05 54 53.589	+46 26 21.76	0.02004
NGC 3227	10 23 30.57	+19 51 54.3	0.00365
NGC 4051	12 03 09.686	+44 31 52.54	0.00216
NGC 4151	12 10 32.574	+39 24 20.88	0.003262
Mrk 50	12 23 24.1414	+02 40 44.401	0.02386
NGC 4593	12 39 39.492	−05 20 39.16	0.008344
NGC 5548	14 17 59.513	+25 08 12.45	0.01627
Mrk 817	14 36 22.134	+58 47 38.93	0.031158
KIC 11178007	18 58 01.111	+48 50 23.40	0.079
Zw 229-015	19 05 25.928	+42 27 39.84	0.027532
Mrk 926	23 04 43.4911	−08 41 08.538	0.04702

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