Continuum Reverberation Mapping of Active Galactic Nuclei: Determination of Optical to IR delay to measure the size of Accretion Disks of Type 1 Seyfert Galaxies.

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1. Abstract

Continuum reverberation mapping (CRM) can be used to measure physical distances in AGN accretion disks. There have been a limited number of studies conducted which measured the continuum reverberation of Type 1 Seyfert galaxies due to a limited number of continuous observations in both the optical and infrared (IR). The goal of this project is to mine data from multiple surveys including: Near Earth Objects Wide-field Infrared Survey Explorer (NEOWISE),Transiting Exoplanet Survey Satellite (TESS), All Sky Automated Survey for SuperNovae (ASAS-SN), Zwicky Transient Facility (ZTF) and the Catalina Sky Survey to find regions of sky that have a maximum amount of observational overlap in the infrared and optical. Once the areas with high temporal coverage are identified, we will look for known Type 1 Seyfert galaxies in those areas and analyze their light curves at multiple wavelengths to determine the time delay between the optical emission to the infrared emission from 0.445 μm - 4.6 μm. This will be used to determine the distance between the optical emitting region and the infrared emitting region.

2. Background

Active galactic nuclei, or AGN, refers to the existence of energetic phenomena in the central region of a galaxy which cannot be attributed to stars (Peterson, 1997). There are multiple classes of AGN, two of which are quasars and Seyfert galaxies. Quasars have a nuclear emitting source that is brighter than all of the stars in their host galaxy by a factor of 100 (~ 10^{13} $L_{\odot}$). Lower luminosity Seyfert galaxies have a nuclear emitting source that is as bright as all of the stars in their host galaxy (~10^{11} $L_{\odot}$) (Peterson, 1997). Khachikian & Weedman (1974) determined that there are two main subclasses of Seyfert galaxies, based on the widths of the hydrogen emission lines. Seyfert galaxies with broad hydrogen emission lines are classified as Type I, and Seyfert galaxies with narrower hydrogen emission lines are classified as Type II.

In the unified model of AGN, a central black hole is surrounded by a rotating accretion disc. The accretion disc is then surrounded by a thick, dusty doughnut-shaped torus. (Peterson, 1997) The dust that constitutes the torus can only occur where temperatures are below the sublimation temperature of the dust. The inner radius of the torus thus depends on the temperature of the accretion disk.

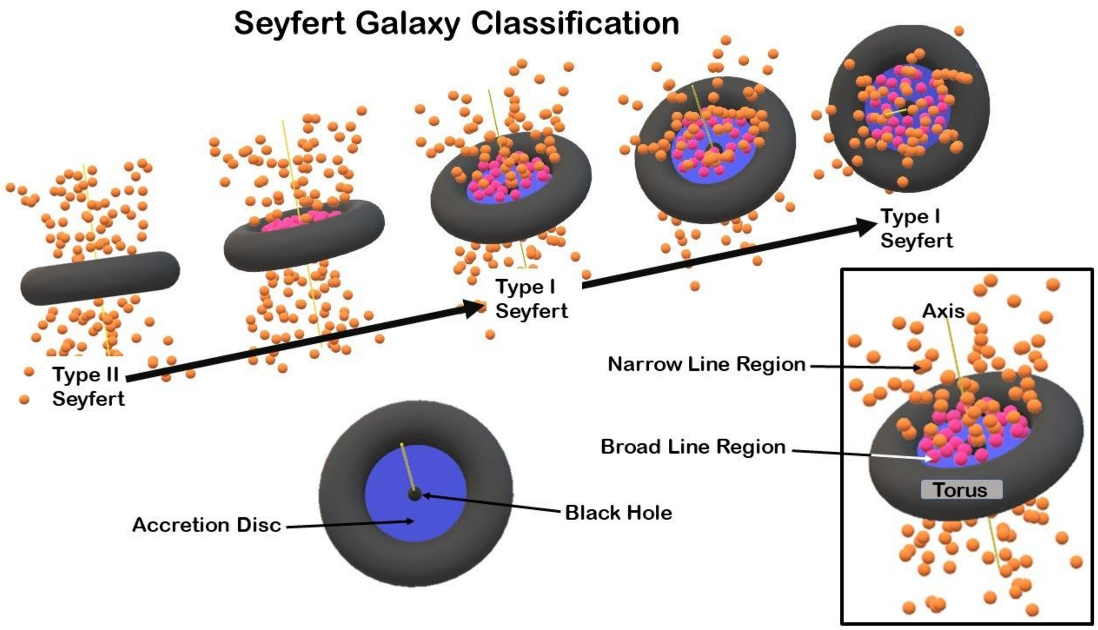

Figure 1: Seyfert Galaxy Identification (N. Boys NITARP) -- *Type I and II Seyfert galaxies viewed from multiple angles. The Broad Line Region is named for fast-moving gas (red dots), near the accretion disc (in blue), that exhibits broad hydrogen emission lines. The Narrow Line Region consists of slow-moving gas (orange dots) that exhibits narrow hydrogen emission lines. In Type II Seyferts, the Broad Line Region is obscured by the surrounding dusty torus.*

Depending on the viewing angle, the torus may either obscure or reveal the features it encloses. Type I Seyfert galaxies are viewed from an angle where the central core and accretion disc is visible. From this angle it is possible to detect the broad hydrogen emission lines emitted by the fast moving gas close to the disc. When a Seyfert galaxy is viewed from the side, with the torus obscuring the central core, it is classified as a Type II galaxy. In this case, the broad hydrogen emission lines are blocked, and only narrower hydrogen emission lines far from the accretion disc are visible (Figure 1).

Active galaxies are too distant for their central regions to be resolved, so determining their structures is a matter of inference. One approach to determining the scale of the disc and torus is Reverberation Mapping (RM), the process of examining time-domain data from the AGN at multiple wavelengths. The technique hinges on the following process: for reasons that are poorly understood, there is significant energy generated from a position directly above the black hole. This energy propagates outward and irradiates the accretion disc and the torus.

As the energy is absorbed by the accretion disc and re-radiated outward, the re-emissions map out the temperature profile of the accretion disc. The closer/hotter emission occurs at shorter wavelengths and the further/cooler region occurs at longer wavelengths (Figure 2).

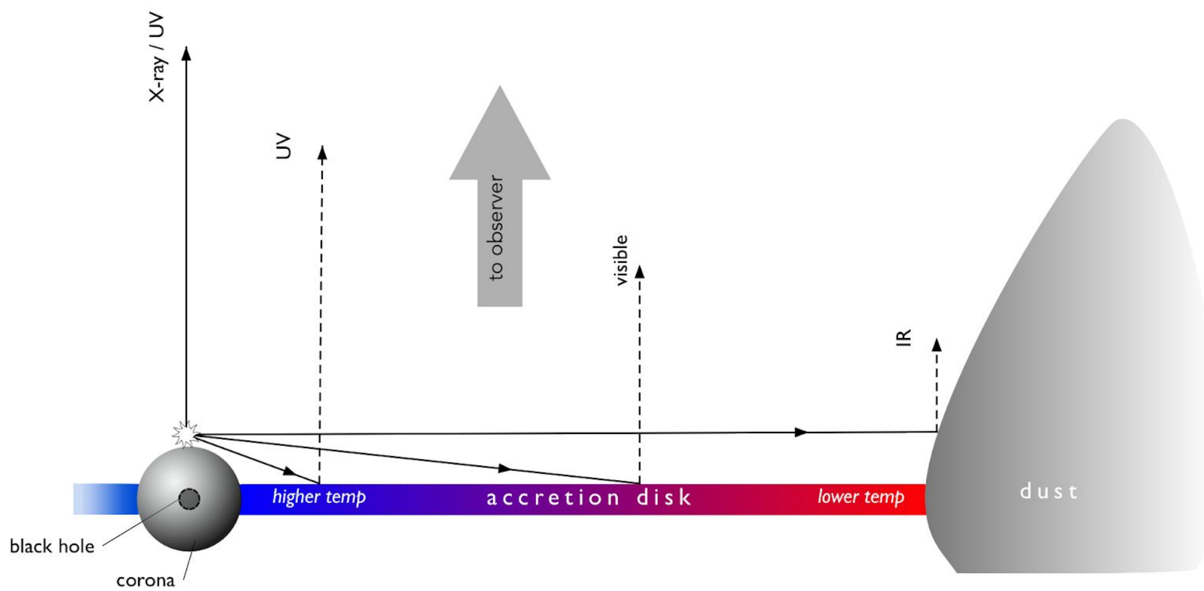

Figure 2: Using RM to map the accretion disc. *Energy is emitted by a central source and absorbed by the accretion disc at varying radii. The wavelength of the light making its way to the observer represents the temperature profile of the disc: photons absorbed by nearby, hotter material are re-emitted at shorter wavelengths, and photons absorbed by more distant, cooler material are re-emitted at longer wavelengths. Re-emission from the dust occurs at IR wavelengths.*

The central source of radiation exhibits significant variability, and this causes variability in the resulting UV, optical and IR re-emissions. Because of the physical separation between the central source and absorbing bodies, there is a transmission-time delay between the primary signal from the central source and the secondary signal from the site of absorption and re-emission. The physical separation from the accretion disc to the torus structure may be determined from the time delay (Δt) between the UV or optical re-emission from the accretion disc and the infrared re-emission from the torus (figure 4). The delay is reminiscent of acoustic reverberation, hence the term RM.

An example of this delay-wavelength relationship can be seen in figure 3 below. A representative set of light curves from Mrk 509 show that variations in the longer wavelengths occur later than variations in the shorter wavelengths. For instance, r-band signals arrive after variations in Swift UVW2.

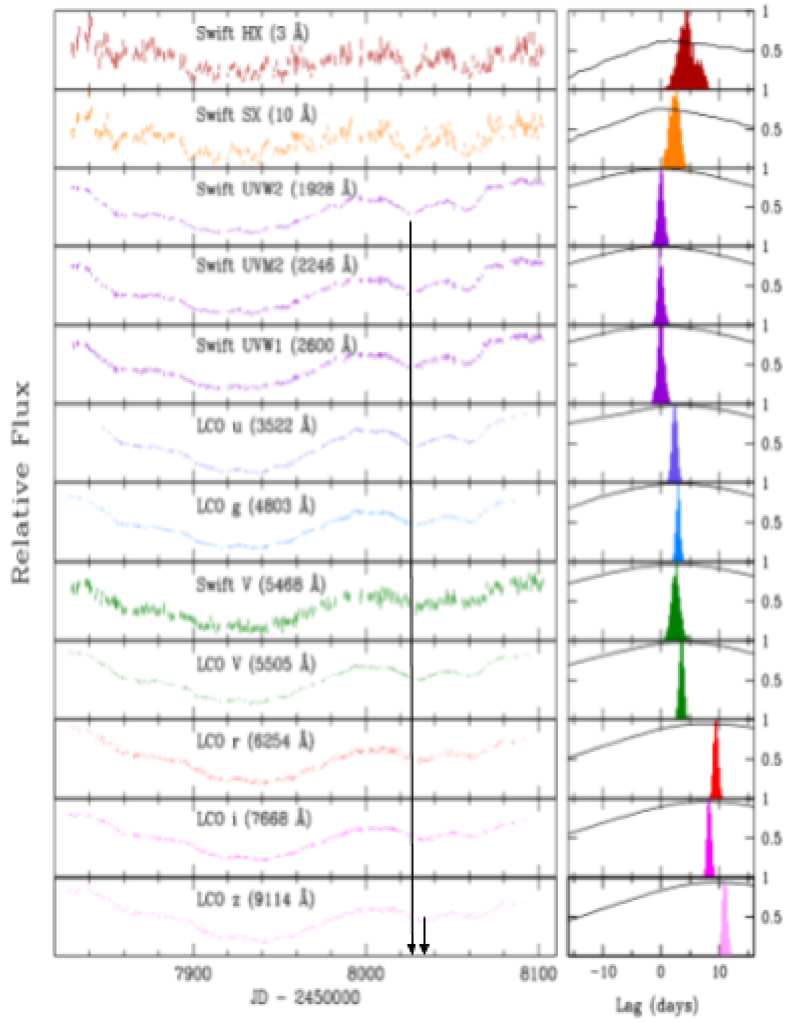

Figure 3: Light Curve Time Delays (R. Edelson, University of Maryland) -- *Starting with the Swift UVW2 light curve there is a unique dip at ~8,022 days. At the LCO z light curve, that same unique dip is at ~8,032 days, which relates to a 10 day delay, indicating a 10 light day distance between the 0.22 μm emitting region of the accretion disc and the 0.91 μm emitting region of the accretion disc.*

3. Scientific Goals

Continuum reverberation mapping will be used to determine the distance from the optical emitting region in the accretion disc to the infrared emitting region in the torus structure for known Type I Seyfert galaxies.

4. Methods and Source Selection

We expect to find that it is easier to correlate light curves from sources with reverberation on shorter time scales, that is to say, with comparatively small Δt between different wavelengths. Shorter timescale variations between wavelengths are associated with smaller accretion discs. This project thus focuses on Seyfert type AGN as their lower luminosities indicate smaller accretion discs, leading to shorter reverberation timescales. Only Type I Seyferts will be used, due to the torus blocking the view of the central core of Type IIs.

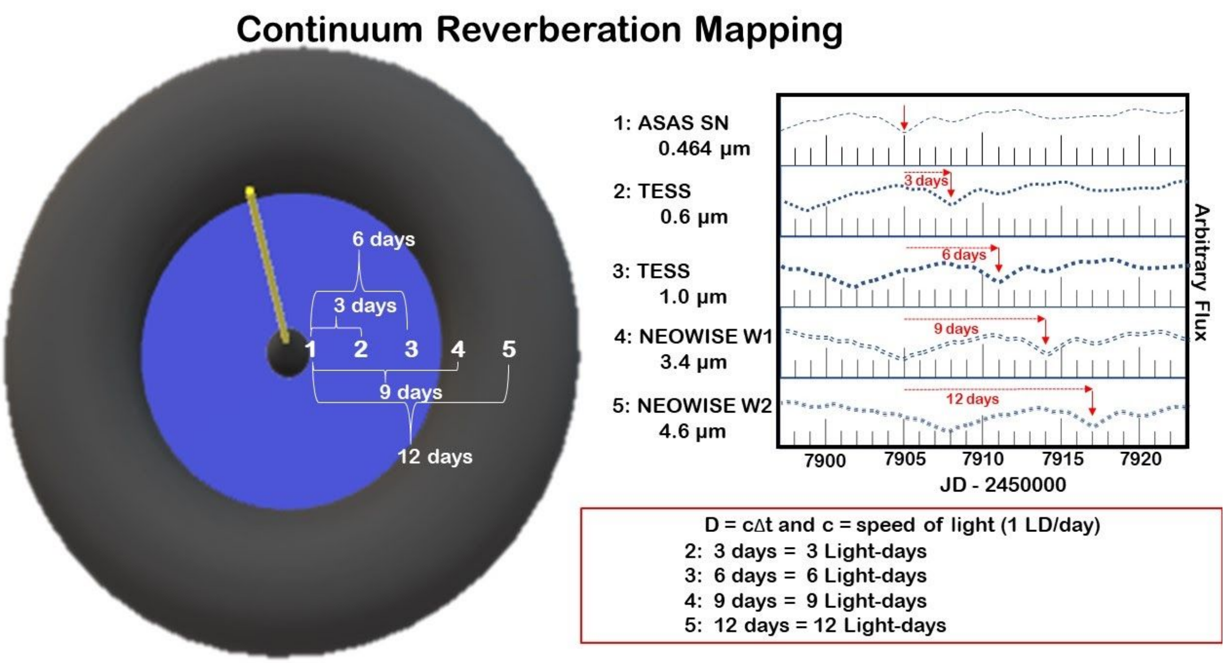

Figure 4: Continuum Reverberation Mapping (N. Boys NITARP) -- *Energy from very close to the black hole propagates outward and irradiates the accretion disc. As the energy is absorbed by the material in the disc and reradiated outward it traces the varying temperature profile of the accretion disc where the closer/hotter emission is re-emitted at shorter wavelengths and the further/cooler region reradiates at longer wavelengths. Ultraviolet wavelengths originate from positions near the center and IR wavelength from distant parts of the disk, or from the torus. Based on the delay (Δt) from a measured 0.464 µm wavelength to the 4.6 µm wavelength, we may determine the distance from the optical emitting region in the accretion disc to the infrared emitting region in the torus structure.*

Low luminosity Type I Seyfert galaxies have been observed by multiple sky surveys including: Transiting Exoplanet Survey Satellite (TESS), Near Earth Objects Wide-field Infrared Survey

Explorer (NEOWISE), All Sky Automated Survey for SuperNovae (ASAS-SN), Zwicky Transient Facility (ZTF) and the Catalina Sky Survey. ASAS-SN is a project using 24 telescopes around the globe, surveying for Supernovae and which has also discovered numerous other bright transients. It surveys the entire sky nightly to 18th magnitude collecting data using a filter spanning 0.464 µm to 0.551 µm. TESS is completing an all sky survey to detect transiting exoplanets. It views a 24 degree by 90 degree strip of the sky for a period of 27 days collecting data using a filter spanning 0.6 µm to 1µm. NEOWISE is a continuation of the Wide-field Infrared Survey Explorer (WISE) project which has surveyed the entire sky at 3.4, 4.6, 12 and 22 µm. With its new main objective to observe near earth objects, NEOWISE continued WISE operations and continuously surveyed the sky from 2013 until 2019. ZTF is a high cadence survey at 0.464, 0.656 and 0.8 µm observing young supernovae and other transients. It has a 47 square degree field and can scan 3,750 square degrees per hour. The Catalina Sky Survey is a project to discover and track Near Earth Objects. It utilizes 3 telescopes which cover up to 4000 square degrees per night at 0.464, 0.656 and 0.7 µm. Utilizing these sources will allow light curves ranging from 0.445 µm to 4.6 µm to be generated.

Data source / filter	Wavelength (µm)
WISE W1	3.4
W2	4.6
TESS	0.6 - 1
ASAS-SN	0.464
	0.551
ZTF	0.464
	0.658
	0.8
Catalina	0.445
	0.464
	0.7

Table 1: Archival data sources and wavelengths.

We will determine the locations on the sky where there is the greatest overlap in sky coverage among the noted surveys, particularly in or near their constant viewing zones, and identify the known Type I Seyferts in those areas from the Veron-Cetty Veron catalog. The light curves for those data will then be analyzed. A foundation to our project is the 2019 study on Mid-IR Variability and Dust Reverberation mapping of Low-z quasars (Lyu *et al.* 2019) which examined 87 quasars and obtained light curves in the optical and IR from ASAS-SN, ZTF, and NEOWISE Surveys. Seventy-seven percent of their quasars had convincing dust time-lag signals (Lyu, et al 2019). An earlier study on Reverberation Measurements of the Dust Torus in four nearby Seyfert I Galaxies (Suganuma, et al 2006) observed the delay between optical and near IR wavelengths, also finding significant time delays between the optical and the infrared.

Objects in the continuous viewing zone (CVZ) will have unbroken light curves. We will start by looking at the CVZs of NEOWISE and TESS and determine the amount of overlap between the two. We will then see if there is any overlapping coverage from the other surveys during this time. Any known low luminosity Type I Seyferts identified within those CVZs will then be analyzed to determine if there is an observable delay from TESS 0.6 μm data to NEOWISE W1 3.4 μm data. Similar efforts will be made for the other optical surveys. The light curves will be analyzed using standard cross-correlation techniques to find a unique pattern that re-occurs at multiple wavelengths with a particular time delay. An example of such time-delay analysis is shown above in figure 3.

If there are no viable samples with observable delays found using the above parameters, then we will expand our selection criteria to any known higher luminosity AGN. If nothing is found, we will continue to allow less continuous overlapping coverage (starting with a couple of days or weeks in a six month period) near the CVZ until a sample of AGN which shows correlated optical and infrared variability is identified.

4. Expected Outcomes

After we use the continuum reverberation mapping technique, using data from NEOWISE, TESS, ASAS-SN, ZTF, and the Catalina Sky Survey we expect to have identified multiple AGN with a measurable delay on the order of a few days to tens of days from 0.464 μm (ZTF, ASAS-SN, and Catalina Sky Survey) to 3.4 and 4.6 μm (NEOWISE W1 and W2). Our primary goal is to find a large sample of AGN with optical and IR monitoring which show reverberation.

Afterwards, we will determine the distance from the optical emitting region in the accretion disc to the infrared emitting region in the torus structure using this optical to IR delay, using the formula $c\Delta t$, where c is the speed of light and Δt is the time delay between the observed unique patterns.

This distance value would represent a step toward a tool for assessing AGN luminosity, as the disk area is correlated to total energy output.

5. Education Outreach

Neal Boys:

- Present the project before the school board at one of the monthly board meetings.
- Present the project at one of the monthly Science National Honors Society meetings.
- Present at a GLAS Star Party.
- Present at the weekly Astronomy Club.
- Implement this research in the Astronomy unit (half of a semester) in my curriculum.
- Prepare an article with my students for the school webpage.
- Present at a local parochial elementary/middle school.

Alyssa McElroy:

- Student Practice Presentation at the Don Harrington Discovery Center one afternoon in Winter 2020 (in preparation for the AAS 2021 Meeting in Phoenix, Arizona)
- STEAM Club Activities, one Monday a month from January 2021 - May 2022
- STEM Class, student drive research projects using public access data, January 2021 - May 2022
- Professional Development for Amarillo Independent School District Spring 2021 or Fall of 2021
- Professional Development with Region 16 to spread NITARP to the Texas Panhandle
- Present methods of research in the classroom Fall 2021 in Fort Worth, TX at CAST (Conference for the Advancement of Science Teaching) hosted by STAT (Science Teacher Association of Texas)

Raghida Sharif:

- Present *Engaging Students in Authentic Astronomy Research* at 2020 Science Teachers Association of New York State (STANYS) Conference
- Lead one-day workshop for Math for America, New York City-based Master Teacher Community, highlighting research process, findings, and how to get students involved
- Share findings and how to get involved with Culturally Responsive Educators (CRE) Professional Learning Group (PLG) of Earth Science teachers at the American Museum of Natural History.

David Strasburger:

- I will share this work and the NITARP program with my colleagues in the science department at Lawrence Academy.
- I will form a student group at my school to develop a pipeline for student research projects in astronomy after this project is complete.

- I will engage with other teachers in my region to present OIRMA findings, and look for possible collaborators for future projects. I will present at:
    - American Association of Physics Teachers, New England Section (AAPT-NES)
    - Lowell Regional Physics Alliance (LRPA)
    - Physics Teacher Education Coalition (PhysicsTEC) at Boston University
- I will pursue a collaboration with the American Association of Variable Star Observers (AAVSO). Conversations started in December 2019 with board president over the possibility of developing an education initiative focused on student research with archival data.

David Temple:

- Share this program and project with fellow science teachers that are part of the EXES Teacher Outreach with the University of Texas Astronomy Department.
- Develop and present a workshop at Space Center Houston's SEEC on a yearly basis. This is an international conference of teachers in all grade levels and subjects not limited to science and math. I have been a presenter at this conference for 18 years and I will add a workshop that I give solely dedicated to NITARP.
- Workshops at the Region 7 Educational Service Center. This is an entity that services school districts and teachers within a geographic region of Texas. They conduct workshops throughout the year and summer.
- I have been a participant in The Phillips Exeter Academy Astronomy Education Conference. This is a summer conference for 14 astronomy educators from across the nation held each odd year summer. The participants are able to share experiences and programs they have worked with. It has a superior support system for continued interaction among the attendees.
- I intend to develop an after school program with students that is designed to work in parallel with other schools. My program will be astronomy based on topic but will have STEM components that integrate basic coding and construction of hardware. My NITARP experience will be a framework for astronomy topics and will hopefully lead to student driven research that can be released and or published.
- The content and processes learned from NITARP will be used to develop new units and pedagogy for my curriculum and for the science department at my school. I am directly involved with the content and lab units for the physical sciences at my school.

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