Using Spitzer Space Telescope data to catalog short-term variable AGN for determining the size of accretion disks.

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Abstract

Current theoretical modelling of the accretion disks around the supermassive black holes (SMBH) at the centers of galaxies, known as active galactic nuclei (AGN), does not match well to that determined by observations. A way to measure the unresolved accretion disk size is through reverberation mapping (RM) of short timeframe variable AGN. Unfortunately, there is a very small sample size of candidate AGN with known short-term variability. These objects have short-period emission events where variations in high energy/short wavelength light close to the SMBH travel outward and are absorbed at larger radii of the accretion disk and re-emitted at lower energy/longer wavelengths. The time delay between initial detection of these variations and the later detections at longer wavelengths provides a way to measure the diameter of the accretion disk. Measuring the size of the accretion disk can be used to derive its luminosity so the AGN can then be used as a standard candle. This in turn can be used to determine the Hubble constant over the vast distances over which the AGN can be observed. In this research we will identify AGN with measurable short-term variability at wavelengths of 3.6 and 4.5 microns over the period of days to weeks which can then be used as targets for RM monitoring to help determine their accretion disk sizes. We propose to create a catalog of reliable AGN candidates with observed short-term variability for lightcurve analysis and reverberation mapping using the Young Stellar Object VARiability survey (YSOVAR) conducted by the Spitzer Space Telescope of multiple star forming regions.

Background

Supermassive black holes (SMBH) are believed to exist at the center of all galaxies (Ferrarese et al 2000, Gebhardt et al. 2000). These SMBH can have a large amount of in-falling gas that forms an accretion disk. The heated gas in the accretion disk surrounding an Active Galactic Nucleus (AGN) gives off radiation across the electromagnetic spectrum. Because gas does not fall into the accretion disk at a steady rate the energy outputs of AGNs vary over periods of years to decades (Peterson 1997). For no AGN is there a resolved accretion disk as they are too far away. The size of the accretion disk is also not well determined at this point in time.

For the purposes of this research we are interested in the presence of short-term events originating very close to the SMBH. The energy output of such short-term flares is triggered by an event that happens on the axes of the SMBH. It is not yet clear what causes these events.

Propagation of the radiation from the flare event produces a unique signal as it is absorbed and re-emitted from the accretion disk (Blandford & McKee 1982). This is observable as a UV emission spike arising from the hot inner disk followed by longer wavelength, progressively time delayed signals from the optical to the infrared (IR). The time delayed pattern in this signal is what eliminates the possibility that this IR spike is from any other emission mechanism of the host galaxy. This time delay can be used to determine the size of the accretion disk without needing to resolve the AGN. Once the size of the accretion disk is determined, it can be used to determine the luminosity of the AGN.

Types of AGN

Not all AGNs will be of use for this investigation. Quasar type AGNs are of extreme luminosity and can outshine the rest of their host galaxies by two orders of magnitude. These are ancient and very distant objects but are not good candidates for producing detectable short-term variability because their accretion disks are very large and take a long time to absorb and re-emit the short wavelength radiation arising close to the SMBH. Seyfert type AGNs are of lower luminosity and tend to have SMBH with smaller accretion disks that shine equally as bright as their host galaxies but can show variability on a shorter time scale. Detection of this short-term variability is how we will identify a target as a Seyfert type AGN.

The continuum emission from the accretion disk excites atoms in the surrounding gas clouds where electrons jump to higher energy levels and then emit photons as they fall back down to lower energy states creating a set of emission lines. The Broad Line Region (BLR) is emission from fast moving gas located close to but above from the accretion disk where the gas is experiencing highly turbulent motions (Urry and Padovani 1995). The Narrow Line Region (NLR) is located further away from the black hole where the gas is moving at slower speeds.

AGNs, both quasars and Seyferts, can be classified as either Type I or Type II with this referring to AGN whose nucleus is visible (thus having spectra with both narrow and broad emission lines), versus those with spectra with an obscured BLR and only narrow line features. These differences are suspected to be due to the viewing angle of the AGN (Figure 1).

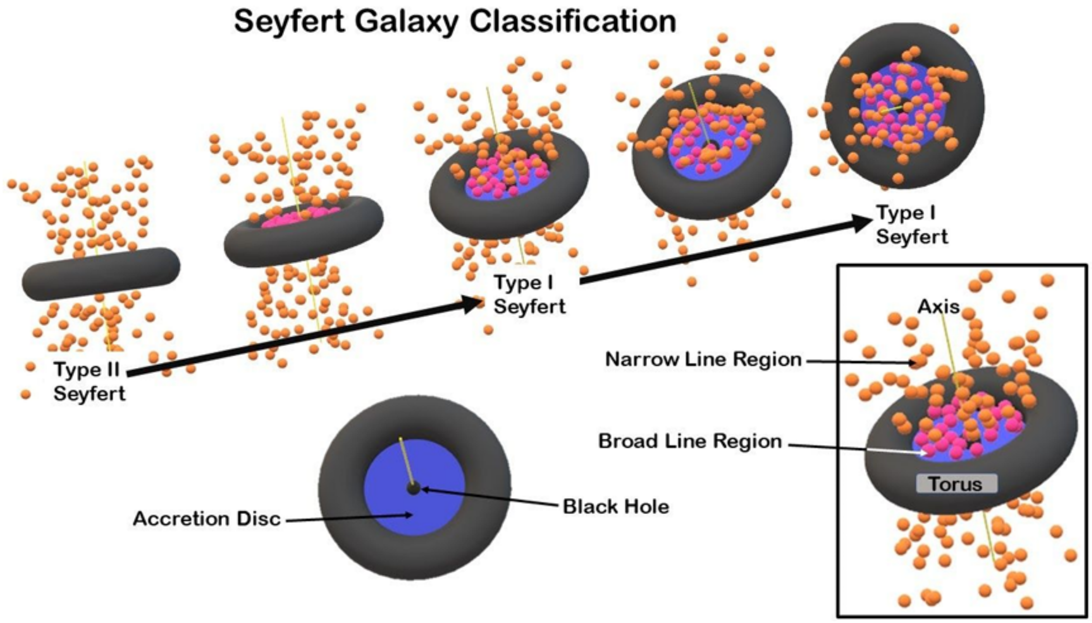

Figure 1: Seyfert Galaxy Identification (N. Boys NITARP, 2020) - Type I and II Seyfert galaxies viewed from multiple angles. The Broad Line Region is named for fast- moving gas (red dots), near the accretion disc (in blue), that exhibits broad hydrogen emission lines. The Narrow Line Region consists 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.

For Type I Seyferts the direct line of sight to their accretion disks makes it possible that short-term variability will be detectable and measurable. Type II Seyferts offer no direct line of sight to the accretion disk and thus obscure any variability that is occurring in the accretion disk.

Of specific interest for this research effort is the occurrence of highly localized flare events, dubbed “lamp post” events, that occur very close to the SMBH of a Type I AGN but above the accretion disk.

The absorption and emission of these “lamp post” flares produce two patterns that can be detected and are useful for determining the size of the AGN’s accretion disk. First, the pattern of increasing time delay correlated to a greater radial distance from the SMBH. Second, the light from the flare is converted to longer wavelengths due to the lower temperatures at the outer radii of the accretion disk. Thus the accretion disk has a radius versus temperature relationship that is imprinted on the reverberated emissions (Figures 2 and 3).

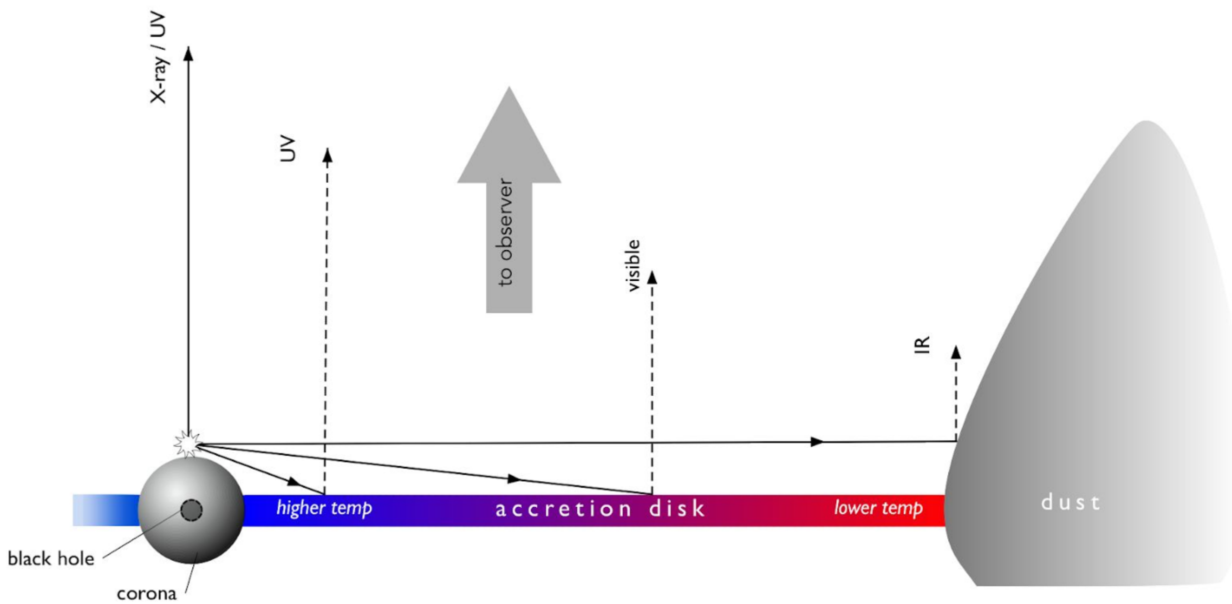

Figure 2: Using RM to map the accretion disc. Energy is emitted by a central source and absorbed by the accretion disc at varying radii. The wavelength of the light making its way to the observer represents the temperature profile of the disc: photons absorbed by nearby, hotter material are re-emitted 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.

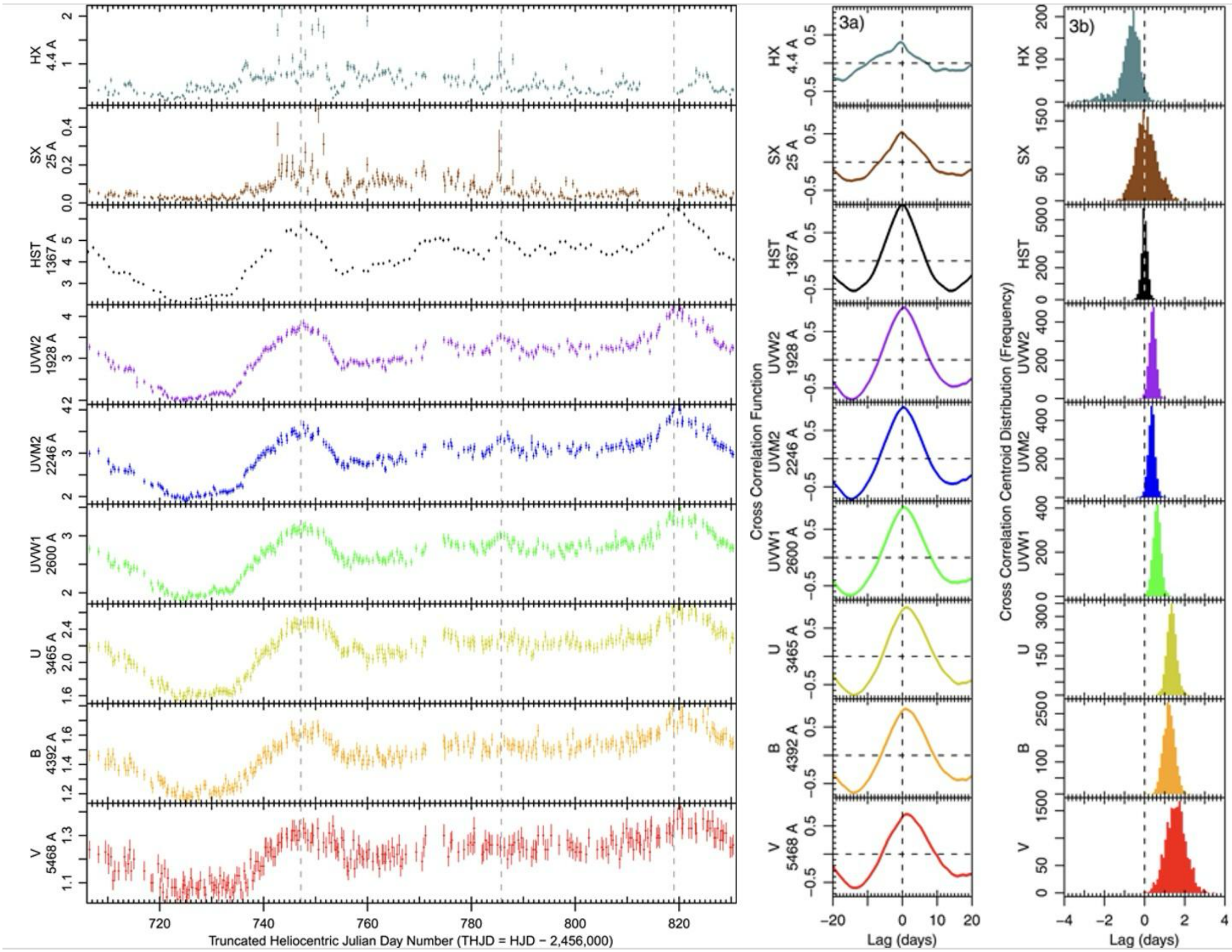

Figure 3: Example of RM of NGC5548. Left side shows light curves generated from Swift and Las Cumbres Observatory data. Right side shows the timing delay of the peak emission detection at each filter calculated from the UVW2 band. (Edelson et al. 2015).

The pattern is continuous from the hot UV-emitting gas from near the SMBH to the outer regions of the accretion disk where it is cool enough for dust grains to form and emit in the IR, currently thought to be on the inner edge of a torus structure. Particularly, once the UV/optical emission strikes the dusty torus it is absorbed and re-emitted in the infrared by dust particles. Because the dusty region has a larger surface area than the accretion disk, all AGN show an infrared excess. This means that they emit more infrared radiation than expected and appear particularly red when plotted on an infrared color-color plot. The pattern of increasing wavelength correlating to the delayed arrival time of variability patterns detected at shorter wavelengths can thus be used as a method to determine the radial size, and thus the surface area of the accretion disk.

Data Reduction

By calculating the change in time from the initial spike of radiation released in the ultraviolet to the re-emission of infrared radiation by dust in the torus, the full radius of the accretion disk can be derived. The larger the accretion disk the longer it will take the flare to be reverberated at longer wavelengths. This is because the hotter the disk, the further the dust sublimation radius will be pushed outward, which is the outer edge of an AGN's accretion disk (e.g. Koshida et al 2014). Therefore, there will be a relationship between the observed radius and the temperature of an AGN accretion disk. Using the relationship between temperature and radius, the luminosity of an AGN accretion disk can be calculated.

It is expected that there will be a wide range of surface areas for AGN accretion disks. Since the radius-luminosity relationship arises from the same type of hot gas physics, once that relationship is calibrated using nearby AGNs, for which distances are known through other means, then it can be applied to all other AGNs to derive their luminosities. The calculated luminosity can be compared to the observed brightness of the AGN to measure its distance from Earth based on the inverse-square relationship of distance and brightness which is the distance modulus equation.

Finding the area of the accretion disk and associating this with the luminosity of the AGN would allow this object to be used as a standard candle and thus as a method with tremendous reach out into the earliest universe and a very accurate way to determine the Hubble constant (e.g. Watson et al. 2011).

Before AGN can be used as standard candles, a good determination of their accretion disk sizes must be made. Hence the scope of this research is to find AGN of Type I that show the short-term variability over days to weeks that make them easier candidates for follow-up for reverberation mapping of their accretion disks to help establish the correct radius vs temperature relationship from which their luminosities could eventually be derived. The Young Stellar Object Variability survey (YSOVAR) Spitzer Space Telescope provides the perfect dataset for this effort due to its high cadence and sensitivity to faint objects.

Methodology

Our work uses data from the YSOVAR observing program which obtained a significant amount of mid-infrared (IRAC 3.6 and 4.5 micron) time series photometry. This work also expands on the work of Kilts et al. (2017), which identified 170 short-term variable AGN candidates in an earlier release of YSOVAR data, and showed that a significant number of Type I AGN with observed short-term variability can be identified in the background of the YSOVAR monitored star forming regions (SFR).

The initial selection of candidate objects will be based on their IR colors. Stern et al (2005) has shown that the IR excess of AGN has a distinct distribution in [3.6]-[4.5] color space greater than 0.5 in Vega magnitudes (Figure 3). Color can also help determine the AGN type as well with Type I being redder by dominating over the host galaxy emission and Type II being bluer due to being dominated by the host galaxy emission. Type I AGN will be selected as they offer the most direct view of the accretion disk of the AGN.

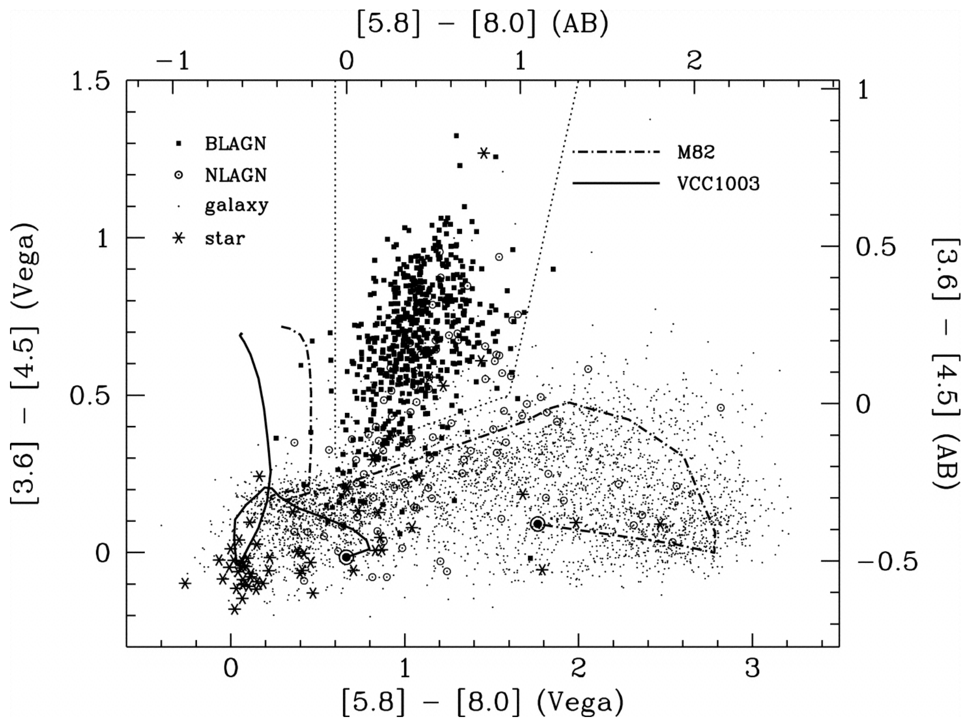

Figure 3: Color-color plot of objects in the IRAC Shallow Survey, a wide-field survey in the Bootes Field. The trapezoidal area defined by the dotted line in the upper center shows a region with a high concentration of broad line AGN. Both AB and Vega magnitudes shown (Stern, et al., 2005)

Further culling of the catalog will make use of the YSOVAR survey dataset (Digital Object Identifier (DOI): 10.26131/IRSA518) and the light curves from Rebull et al. (2014) so as to discard objects that have light curves consistent with being YSOs. YSOs tend to have periodic patterns of variation while AGNs do not.

We will visually confirm remaining candidates using higher resolution optical images available in the IR science archive (IRSA) to ensure they are extragalactic sources based on the object's non-spherical appearance. We will correlate this with the GAIA DR3 astrometry catalog and remove objects identified as stellar based on proper motion and parallax, as AGN do not show proper motion or parallax, to further increase catalog reliability.

As a final step, for the remaining sample, we will identify and summarize the variability based on scatter from the mean over short time-periods (days to weeks). This is preparation for the follow up work that will require the use of simultaneous optical and IR light curves from other telescopes for reverberation mapping of the AGN's accretion disks.

Our resulting catalog will contain reliable candidates of Type I Seyfert AGN with observed short-term variability for subsequent reverberation mapping.

Expected Outcomes

We will be searching for short-term variable AGN within the YSOVAR survey conducted by the Spitzer Space Telescope (Rebull et al, 2014) and, based on Kilts et al (2017), we expect to find tens of short-term variable AGN hidden in plain sight within the IC 1396 region, otherwise known as the Elephant Trunk Nebula. This region is favorable due to having a high cadence of data. We will be using light curve data in the 3.6 and 4.5 micron bands to identify AGN which vary on time-scales of less than 40 days, as that was the timespan of the YSOVAR data. These AGN are ideal candidates for follow-up reverberation mapping.

This is the first step in refining our understanding of the structure of AGN and ultimately being able to correlate the size of an AGN's accretion disk to its luminosity. If such a correlation can be defined, then AGN can serve as standard candles to help map the expansion of the universe even at large distances.

Education and Outreach Activities

Ben Senson
Madison College and MMSD Planetarium, Madison, Wisconsin

- Summarize the research experience and findings for a monthly meeting of the Madison Astronomical Society and for the Middleton and Vel Phillips Memorial high school astronomy club meetings.
- Schedule an interview with local media
- Integrate research results into the classroom and lab activities of the Astronomy Stars & Galaxies course at Madison College.
- Produce a MMSD Planetarium show for one of our monthly public shows focused on the science of black holes.
- Collaborate with Lauren Albin to produce a 5 minute summary of the science related to this project as it relates to an introduction to me as a person.

Meredith Cullen
UMS-Wright Preparatory School, Mobile, Alabama

- Offer a workshop about my experiences in the program and implementing higher level research opportunities for high school students to local secondary teachers.
- The students and I will present the project before the UMS-Wright Preparatory School Board of Trustees at one of the monthly board meetings. The students and I will also present the project before members of the UMS-Wright Preparatory School faculty.
- Interview with local media including student participants

Lauren Albin
Young Harris College and O. Wayne Rollins Planetarium, Young Harris, Georgia

- Advise students on how to locate AGNs in archival data and demonstrate how archival data can be used to advance science.
- Presentation to administration on how archival data can be used to advance student research projects in astronomy
- Planetarium presentations for the general public on progress of HIPS AGaiN project, including student presenters.
- Collaborate with Ben Senon to develop a planetarium short on AGNs and reverberation mapping.
- Continue to do archival research using IPAC and NASA databases.

Kevin Molohon
Champlin Park High School, Champlin, Minnesota

- Be an advisor for students doing research using archived data.
- Present to my District Colleagues about NITARP and students doing authentic science research.
- Present at various State and National Conferences about NITARP and having students do authentic science research.

- Continue to do archival research based on the knowledge and skills developed through the NITARP experience.
- Create a cohort of science teachers who want to learn how to use archival data to do science research.
- Blow up Science… do a presentation in my district's inflatable planetarium focused on Black Hole science.

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