Exploring the AGN Accretion Disks Using Continuum Reverberation Mapping

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Abstract

In the innermost regions of Active Galactic Nuclei (AGN), matter is understood to be flowing onto the Supermassive black hole (SMBH), which forms an accretion disk. This disk is responsible for the optical/UV continuum emission observed in the spectra of AGN. Reverberation Mapping of the accretion disk using multiple bands can yield the structure of the disk. The emission is expected to be of the black body type peaking at different wavelengths. Hence, depending on the temperature of the disk, continuous, simultaneous monitoring in multiple wavelength ranges to cover hotter inner regions and cooler outer regions can yield the structure and temperature profile of the accretion disk itself. In this study, we present initial results from our accretion disk reverberation mapping campaign targeting AGN with Super High Eddington Accreting Black Holes (SEAMBH). Our analysis on one of the sources, IRAS 04416+1215, based on the broadband observations using the Growth India telescope (GIT), reveals that the size of the accretion disk for this source, calculated by cross-correlating the continuum light curves is larger than expected from the theoretical model. We fit the light curves directly using the thin disk model available in JAVELIN and find that the disk sizes are approximately four times larger than expected from the Shakura Sunyaev (SS) disk model. Further studies are needed to understand better the structure and physics of AGN accretion disks and their role in the evolution of galaxies.

Keywords: accretion, accretion discs, galaxies: active, galaxies: Seyfert, galaxies: nuclei, quasars: supermassive black holes

1.   Introduction

Active galactic nuclei (AGN) are among the most luminous and energetic objects in the universe. They are powered by the accretion of matter onto supermassive black holes at the centres of galaxies (Salpeter, 1964). The accretion process occurs in a disk-like structure known as an accretion disk. These disks are composed of gas and dust that orbit the black hole, gradually spiralling inward and releasing energy in the form of radiation. Understanding the properties of these disks, including their size, is crucial for understanding the behaviour of AGN and their role in the evolution of galaxies (Kormendy and Ho, 2013).

Reverberation mapping is a powerful technique for studying the inner structure of AGN (Bahcall et al., 1972; Blandford and McKee, 1982; Cackett et al., 2021). It involves measuring the time delay between variations in the continuum emission from different regions. This time delay provides a measure of the continuum emitting region. By analyzing these time delays for multiple AGNs, it is possible to measure the mass of the black hole residing at the centre (Dalla Bontà et al., 2020). Reverberation mapping measurements have also yielded a relation between the luminosity of the AGN and the size of the Broad Line Region (BLR), the so-called $R - L$ relation (Kaspi et al., 2000; Bentz et al., 2009; Du et al., 2016). Accretion disk reverberation mapping, which used the multi wavelength light curves to measure the lags between the various regions of the accretion disk, has been used to infer the disk sizes for a variety of objects, (Edelson et al., 2015; Starkey et al., 2016; Hernández Santisteban et al., 2020; Kara et al., 2021, etc.). These studies measured the inter-band lags from X-ray to the optical IR wavelengths to generate a complete profile of the accretion disk. However, only a handful of objects have such intensive measurements. Ground-based studies have also proven successful in constraining the accretion disk sizes for about a hundred AGN, although covering a smaller wavelength range (Jiang et al., 2017; Mudd et al., 2018; Homayouni et al., 2019; Jha et al., 2022; Guo et al., 2022a).

The theoretical SS disk model has been widely used to describe the accretion disks (Shakura and Sunyaev, 1973). However, results from observations have yielded that the size of the accretion disk in AGN is larger than the expectations from this model (Starkey et al., 2016). This implies that either the SS disk model does not hold for these objects or additional complexities are involved. The disk sizes being larger than predicted by standard models also imply that some key ingredients in the classical thin disk theory may need to be added.

An interesting subset of AGN are the objects accreting at super Eddington rates (see Wang et al., 2013). These objects have been observed to be accreting at many times the Eddington Accretion rates. Through reverberation mapping campaigns, the BLR sizes for these objects are significantly smaller than the empirical RL relation observed in other AGN studies (Du et al., 2016). How their accretion disk sizes scale with respect to the other AGNs remains to be seen. In order to study the accretion disk structure in these objects, we are carrying out a disk reverberation mapping campaign in the optical wavelength.

In this work, we present initial results from the accretion disk reverberation mapping campaign of AGN, that we perform using data from the GROWTH India Telescope (GIT). This paper is structured as follows: Section 2 presents the sample being used for this study and the

details of the observations. Section 3 presents the methods being used for our study, while Sect. 4 presents the initial results for one of the sources. We present the discussion in Sect. 5 followed by conclusions in Sect. 6.

2. The Sample and Observations

We have compiled a sample of 18 AGNs with high accretion rates obtained from Du et al. (2015). The SMBH masses for these AGNs are well constrained through the reverberation mapping studies. The BLR sizes for these sources are significantly lower than predicted by the radius luminosity relation, which has been observed to be very tight for the other AGNs with RM measurements. Whether this peculiar behaviour is seen in the accretion disk measurements of such AGN is unexplored at the moment. To map the accretion disk of these AGNs, we have started a large program entitled: "Investigating the central parsec regions around supermassive black holes" (INTERVAL). In this campaign, we are performing multi-band (u, g, r, i, and z) monitoring of AGNs using a 70 cm GROWTH India telescope (GIT) and 50 cm telescope at the Indian Astronomical Observatory (IAO) in Hanle, Ladakh.

The 70 cm GIT operates in robotic mode through a queue-based observation schedule. Calibration frames are taken every night, and the automatic pipeline for photometry yields the aperture and the Point Spread Function (PSF) based magnitudes for the objects (Kumar et al., 2022). The observations for four of the AGNs in our sample have been completed with GIT while we continue the observations for the remaining sources from our sample. The data are reduced and calibrated using standard procedures to produce light curves for each object in each band using PSF photometry. We then perform cross-correlation analysis to measure the time delay between variations in the continuum emission arising from the accretion disk.

3. Methods

We aim to estimate the disk sizes in the AGN by measuring the interband lags between the continuum emission from different regions of the accretion disk represented by the u, g, r, i, and z band light curves. We employ two methods to derive the interband lags: JAVELIN and ICCF. We also use the JAVELIN thin disk model developed by Mudd et al. (2018) to fit the light curves directly to a disk model.

JAVELIN is a method that models the AGN variability as a Damped Random Walk (DRW) and employs a Bayesian approach to infer the posterior distribution of the lags and their uncertainties (Zu et al., 2011). This method has been demonstrated to be accurate and reliable as compared to the other methods being used (Li et al., 2019). ICCF is another method that computes the cross-correlation function of the light curves and identifies the peak of the function as the lag (Peterson et al., 1998). This method has been extensively applied in reverberation mapping studies and performs well when the data quality is high (Sun et al., 2018).

We compare the outcomes of both methods to assess their consistency and robustness. We also conduct various tests to evaluate the validity of our measurements and respective errors.

Table 1: The light curve statistics for IRAS 04416+1215 being used for this study.

Bands	Date range (MJD)	Points	Median PSF (mag)	Error	Average cadence (days)
g	2459835–2459945	24	16.44	0.04	4.5
r	2459835–2459945	24	16.18	0.04	4.5
i	2459835–2459945	21	15.71	0.04	5.2
z	2459835–2459945	26	15.60	0.05	4.2

We run Markov Chain Monte Carlo (MCMC) iterations in JAVELIN with the parameter values nwalkers = 1000, nburn = 500, and nchain = 1000. These parameters are sufficient, and increasing them does not affect the results. Similarly, for the ICCF method, we run 5000 iterations of Random Subset Sampling and flux Randomization in ICCF. This enables us to obtain the lags between the light curves and their associated uncertainties.

4. Results

The observations for the first four sources in our sample, namely IRAS 4416+1215, Mrk 382, Mrk 42 and Mrk 1044, are complete, and in this work, we report on the initial results obtained for IRAS 04416+1215. It is located at a redshift of 0.0889 and categorized as a hyper Eddington source (Tortosa et al., 2022). For this source, the observations are available for a total of 27–30 points in each band. The average photometric error is about 0.04 magnitudes in all the bands. We reject the outlier points whose magnitude is greater or less than 2 magnitudes from the mean magnitude. This reduces about two to four data points in each band. We use the PSF light curves for our analysis of this source. We note that the source is not prominent in the u band. Hence we use only the four band light curves −, namely the g, r, i, and z bands, for our analysis (see Table 1). The object appeared to be variable in all 4 bands (see Fig. 1). The inter-band lags are measured with respect to the shortest wavelength available, which happens to be the g-band.

First, we estimate the lags using JAVELIN (Zu et al., 2011). It models the driving light curve as a DRW process, building a posterior distribution for the variability amplitude (σ) and the damping timescale (τ) (see Fig. 2). It then shifts, scales, and smooths the light curve to generate a responding light curve and builds a distribution of the lag between the two light curves. We obtained a lag of $0.09^{+1.05}_{-1.07}$ days between the $g-r$ bands, $6.93^{+3.69}_{-9.11}$ days between the $g-i$ bands and $6.26^{+5.23}_{-5.78}$ days between the $g-z$ bands. Noticeably, the $g-r$ band lag is larger than the $g-i$ band lags, although the uncertainties are significantly higher at the 1σ level.

We also implemented the ICCF method, a widely used method for the lag measurements (Peterson et al., 1998). It does not assume an underlying model, but rather it interpolates between the gaps and then cross-correlates the individual points to generate a distribution for the cross-correlation function. The uncertainties are estimated using flux randomization (FR) and random subset selection (RSS). We use the centroid of the CCF to estimate the lag. We obtain a lag of $2.9^{+4.9}_{-4.9}$ days for $g-r$ band, $3.5^{+5.1}_{-4.9}$ days for $g-i$ band and $7.0^{+3.3}_{-3.5}$ days for $g-z$ bands
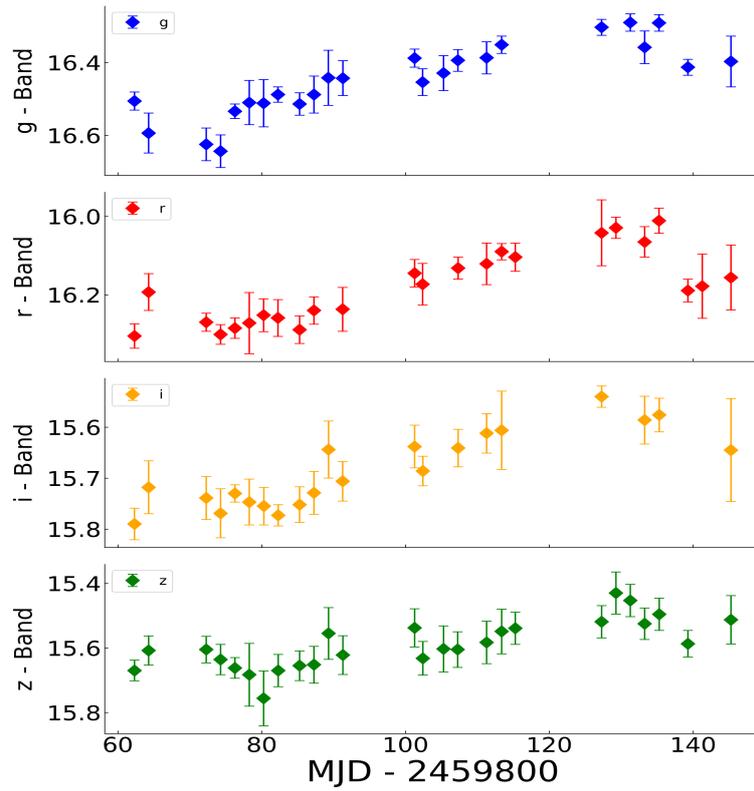
Figure 1: The *g*, *r*, *i*, and *z* band light curves for IRAS 04416+1215 were obtained using the Growth India Telescope (GIT).
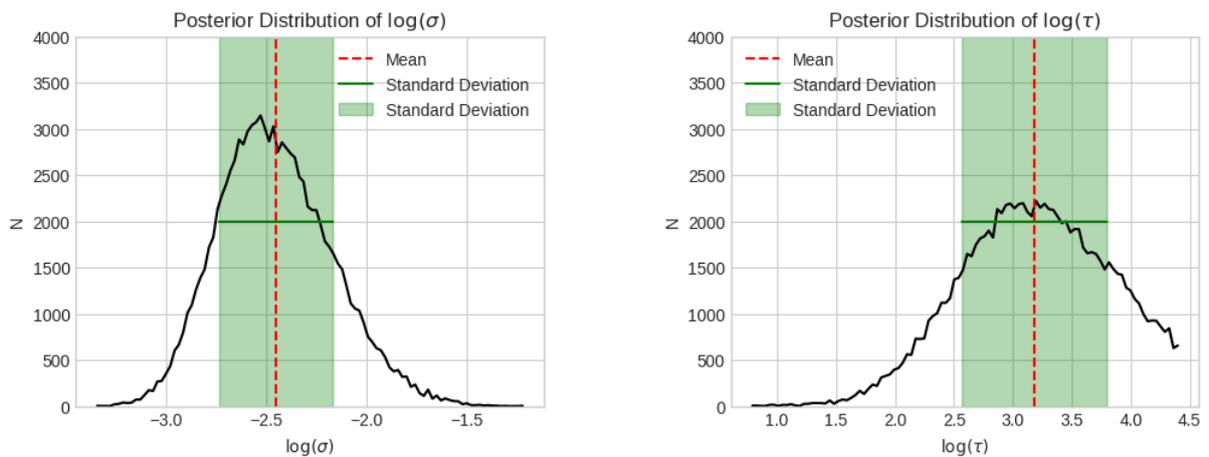

Figure 2: Posterior distribution for the logarithms of the amplitude of variability (σ) and the damping timescale (τ) obtained for the driving continuum light curve, which we assume to be the *g*-band light curve.
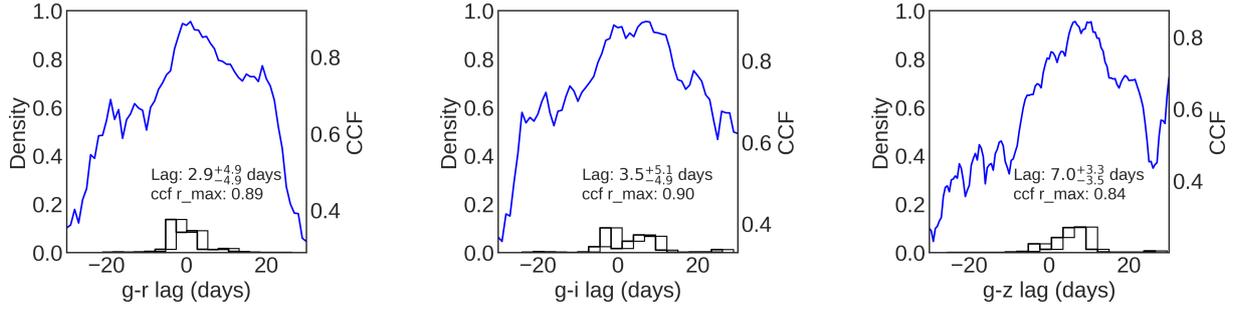
Figure 3: The Cross Correlation Posterior Distribution (CCPD) along with the correlation coefficient for IRAS 04416+1215 for the $g-r$, $g-i$, and $g-z$ bands are shown here.

Table 2: Estimated lags using JAVELIN and ICCF (in days) for IRAS 04416+1215.

Bands	JAVELIN lags	ICCF Lags
$g-r$	$0.09^{+1.05}_{-1.07}$	$2.9^{+4.9}_{-4.9}$
$g-i$	$6.93^{+3.69}_{-9.11}$	$3.5^{+5.1}_{-4.9}$
$g-z$	$6.26^{+5.23}_{-5.78}$	$7.0^{+3.3}_{-3.5}$

(see Fig. 3 and Table 2). The increasing lags with the increase in wavelength are seen using the ICCF method. We find that the obtained lags through both methods are slightly different with higher uncertainties, especially with the measurement using JAVELIN.

We notice that the uncertainties in the lag estimates are quite large using both JAVELIN and the ICCF methods. One of the primary reasons could be the cadence of the light curves. The median cadence that we achieve is about 4-5 days, which makes it difficult to recover shorter lags. For other sources in our sample, we aim to get denser sampling so as to recover lags with better precision.

Taking the advantage of our multi-band data set, we fit the light curves using the JAVELIN thin disk model. The g-band light curve is assumed to be the driving light curve, while the r, i, and z-band light curves are responding light curves. The disk model gives us the disk size at the driving wavelength, which is the g-band rest wavelength. We fixed the β parameter to 1.33 while calculating the disk size, which implies a SS disk. The disk size at the g-band rest wavelength is estimated to be $2.96^{+3.28}_{-2.03}$ light days.

We also calculate the disk size R size at the g-band rest wavelength λ_0, using the equation in Mudd et al. (2018), based on the SS disk model as:

$$\frac{R_{\lambda 0}}{\mathrm{cm}} = 9.7 \times 10^{15} \left(\frac{\lambda_0}{\mu\mathrm{m}}\right)^{\beta} \left(\frac{M}{10^9 M_\odot}\right)^{2/3} \left(\frac{L}{\eta L_\mathrm{E}}\right)^{1/3} \tag{1}$$

where λ_0 is the wavelength at which the disk size is estimated, $\beta = 4/3$, M is the SMBH mass in units of Solar mass ($M_\odot$), and L is the luminosity obtained from (Du et al., 2015), L_E is the
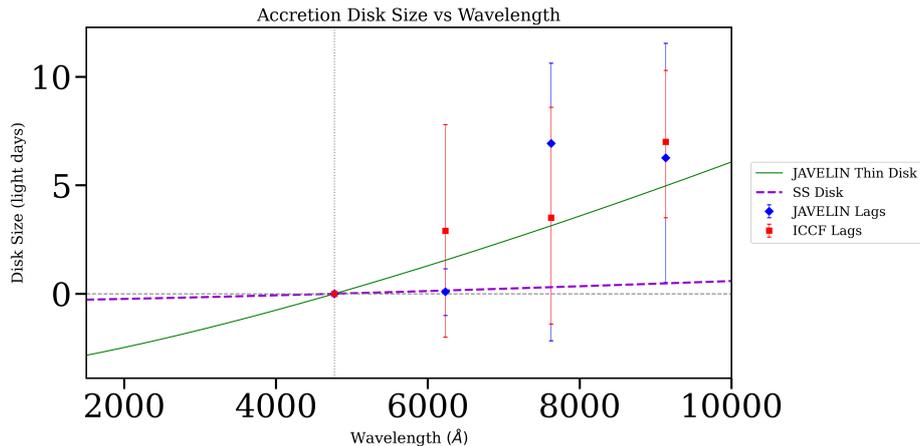
Figure 4: The relation between the accretion disk size and the wavelength for IRAS 04416+1215. We use the *g*-band rest wavelength as the reference wavelength for estimating the disk sizes. The green solid line shows the extrapolation on the JAVELIN thin disk model. The blue points show the lags obtained using JAVELIN, while the red points show the lags obtained using ICCF. The dashed purple line shows the standard SS disk model prediction for this source.

Eddington luminosity. We take the efficiency parameter η as 0.1, as has been used in previous works.

We find that the disk size obtained using the JAVELIN thin disk model is four times larger than what we would obtain based on the theoretical prediction of the SS disk as given in Eq. (1). If we plot the thin disk model, we find that the calculated lags lie near to the curve generated by this model, implying that the disk is following the 4/3 scaling relation, but the size of the disk is larger than the prediction for the SS disk (see Fig. 4).

5. Discussion

In this study, we present initial results from the INTERVAL campaign measuring the accretion disk sizes for SEAMBH AGN using the GIT. For one of the sources, we measure the inter-band time delays using both the JAVELIN and ICCF methods. Our analysis reveals that the size of the accretion disks for this object is larger than expected from the theoretical SS disk model. Our findings are consistent with recent studies that have found that AGN accretion disk sizes are generally larger than predicted by standard models (Starkey et al., 2016; Fausnaugh et al., 2018; Edelson et al., 2019). Recent studies using optical data from the Zwicky Transient Facility have also found that the accretion disk sizes for AGN are multiple times larger than predicted by the standard SS disk model (Jha et al., 2022; Guo et al., 2022b,a).

To address this discrepancy, it has been proposed that the larger-than-expected accretion disk sizes found in AGN studies are primarily due to the neglect of reddening (Gaskell, 2017). They estimated that neglecting internal extinction leads to an underestimate of the luminosity at 1200 Å by a factor of seven, and therefore the size scale of the accretion disk has been

underestimated by a factor of about 2.6. This is similar to the accretion disk size discrepancy found in other studies and supports the proposal that internal reddening plays a significant role in explaining the discrepancy. We aim to estimate the reddening for our sources, to test whether this phenomenon affects the lag estimates. The contribution of the Diffuse Continuum (DC) to the continuum light curves has also been observed (see Chelouche et al., 2019), which can have a direct consequence of increasing the inter-band continuum lags on account of the contribution from the BLR.

Another possibility is that the accretion disks in AGN are not geometrically flat but instead have a slim (Narayan and Yi, 1995) or even a clumpy structure, which would not agree well with the SS disk model. Analytical modelling of the accretion disk will be very helpful in resolving this discrepancy. The results suggest that there are some key ingredients in the classical thin disk theory that need to be added. Further studies are needed to investigate this possibility and to better understand the structure and physics of AGN accretion disks.

While the BLR sizes for SEAMBH AGN are estimated to be lower than estimated from the $R - L$ relation, we also want to explore whether this phenomenon is true for the accretion disk sizes. However, our result for one of the SEAMBH sources, namely IRAS 04416+1215, shows that the disk size is about four times larger than the SS prediction, a phenomenon observed for the other AGNs as well. We continue to monitor these AGNs in order to better understand their accretion disk structure.

6.   Conclusions

We present results from our accretion disk reverberation mapping campaign targeting AGNs with Super High Accretion Rates. Initial results for one of the sources, IRAS 04416+1215, identified as a hyper Eddington accreting source, are presented. Here are the conclusions from this work.

1. The interband continuum lags analysis for IRAS 04416+1215 reveals that the size of the accretion disk is larger than expected from the standard SS disk model.

2. We fit the light curves directly using the thin disk model available in the JAVELIN package, which reveals the disk sizes to be about four times larger than the prediction of the theoretical SS disk model.

3. Our findings are consistent with recent studies that have found that AGN accretion disk sizes are generally larger than predicted by the SS disk model. These results suggest that there can be some key ingredients in the classical thin disk theory that need to be added.

4. For further understanding, we continue to monitor the sample of SEAMBH AGN in order to get the accretion disk size estimates based on continuum reverberation mapping. Such studies are needed to understand better the structure and physics of AGN accretion disks and their role in the evolution of galaxies.

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Further Information

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Conflicts of interest

The authors declare no conflict of interest.

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