TNT photometric reverberation mapping analysis of high-redshift quasars

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Abstract. Supermassive black hole (SMBH) mass determination is essential for understanding the galaxy-SMBH co-evolution. Photometric reverberation mapping (PRM) has been proposed as an alternative to the traditional method, spectroscopic reverberation mapping (SRM), which has limitation to only relatively low redshift, $z$, and bright objects. However, the most common and important sample of high-$z$ active galaxies known as quasar or QSO have its populations peak at around $z \approx 2-3$ thus out of reach for the SRM. We carried out a proof-of-concept campaign of quasar PRM using the 2.4-m Thai National Telescope (TNT) between 2015-2018. Such a study is important to inform a future wide-field high-cadence survey such as the Large Synoptic Survey Telescope (LSST). Our main sample contains 10 quasars at redshift $z \approx 0.7-1.2$ with $r_{SDSS} = 19.7-20.7$ mag, selected from the SDSS data release 10. The processed data and light curves were analysed using the discrete cross-correlation function (DCF). We used Monte Carlo (MC) simulations to model the noise characteristics and non-uniform coverage of our data as well as to verify robustness of the DCF results. Our analyses show a significant detection of lag time between continuum and broad-line emission bands of the quasar SDSS J081506.93+254124.7 ($z = 1.18$, $r_{SDSS} = 20.5$ mag). The estimated broad line region (BLR) distance is $125 \pm 20$ light-day which equate to the estimated SMBH mass of $(4.3 \pm 2.0) \times 10^8 M_\odot$.

1. Introduction

It is generally accepted a supermassive black hole (SMBH) resides at the centre of every galaxy [1-2]. The origin of the SMBH is not justify up to now, however we found its the main engine made luminous active galactic nucleus (AGN). Nevertheless, not every galaxy is active unless gas gravitate into the SMBH. Conserving angular momentum of gas pulled form an accretion disk and had synchrotron radiation as electromagnetic waves before missing in the dark area. Then this energy was transferred to outer gas region, BLR and re-emitted. This activity is proceed since primordial universe and the rate related with SMBH mass. Studying growth rate of SMBHs masses could represented galaxy evolution in terms of co-evolution [3].

Direct measurement of BH mass requires high spatial resolution which is not possible for distant objects. Quasar spectrum observed composite of continuum line resulting from accretion disk alternately with broad emission line resulting from BLR. Both of them are cannot resolve therefore the disperse of velocity was used instead of velocity. Under the concept that BLR gas motion is virialized, implied that the kinetic energy is 1/2 of potential energy for scalar term when the system is in gravitational equilibrium. The SMBH mass can be estimated using
equation (1) [4],
\[ M_{BH} = f \frac{R_{BLR}v^2}{G}, \]  
where \( f \) is virial coefficient explained geometry of the BLR (\( f=1 \) means BLR is virialized), \( G \) is universal gravitational constant, \( v \) is velocity dispersion of BLR and \( R_{BLR} \) is the distance from accretion disk to BLR. Regularly \( v \) calculated using full width at half maximum (FWHM) of broad emission line from single-epoch spectrum. \( R_{BLR} \) is estimated by reverberation mapping technique or radius-luminosity (R-L) relation. For nearby galaxy and very low-\( z \) AGNs, \( R_{BLR} \) was precisely estimated using spectroscopic reverberation mapping (SRM) technique. However, this technique is inapplicable for mostly AGNs which are very bright and faraway known as quasars which have their population peak at \( z \approx 2-3 \). Photometric reverberation mapping (PRM) was proposed to measure BLR distance for these high-\( z \) quasars [5].

2. Observation
The facility for our observation is 2.4-m optical telescope at Doi Inthanon (Latitude: 18° 34’ 25.4″ N, Longitude: 98° 28’ 56.1″ E, Elevation 2457 m). Our location disturbed by high humidity almost of the year which is limited observable time maximum at 6 months a year. Requirement of PRM technique doing with multi-epoch observation. Consequently, our selection target limited lag-time calculated using R-L relation equation from [6] ≤ 60 light-day to suit the length of Thai National Telescope (TNT) observing season. Our main filters used for tracking broad emission flux is SDSS-r and continuum flux is SDSS-g or SDSS-i depends on spectrum profile. The detailed description of selection criteria and target priority of the survey in this work are described by Pongsupa G.

2.1. Magnitudes calculation
Quasars photometric observation data were basically reduced and analysed using IDL pipeline. The extraction of signal images selected with signal to noise ratio (S/N) \( \geq 5\sigma \). Then, matched our catalogue with SDSS using STILTS program to collect standard magnitudes and any important information. Accuracy of magnitudes calculation is crucial for estimating BLR distance using magnitudes cross correlation. To correct instrumental magnitudes to standard magnitudes requires a constant called zero point (ZP). For not variable stars the corrected magnitudes must be the same in every measurement. In order to get ZP, we matched our stars by coordinate with known stars from reliable source, SDSS and compared our instrumental magnitudes with standard magnitudes. Then substitute the median of ZP into equation \( m_{std} = m_{int} + ZP \) to calculate standard magnitudes. We calculated ZP per each quasar and filter resulting of the fluctuation of weather. The calculated ZP denoted by figure 1 (a) and the values are \( \approx 22-25 \). A side from corrected standard magnitudes, ZP is also refers to the magnitudes limited of the observation by instrument. In practical, the maximum magnitude observable must be lower than the sky magnitude which our location sky magnitude is \( \approx 22 \) mag. The calculated magnitudes compared with SDSS denoted by figure 1 (b, c and d), with the root mean square (rms) error for g-band=0.12 (b), r-band=0.08 (c), and i-band=0.11 (d) respectively.

3. Discrete cross correlation function
Our photometric observation aim to estimate the BLR distance from real observation which is take shorter time than spectroscopic technique. Under the hypothesis that BLR gas re-emitted by transferred energy from accretion disk thus broad emission line magnitude expected to change after continuum line magnitude caused by light travel time. This time delay refers to BLR distance which can estimate by crossing 2 set data to find their correlation. Discrete
cross correlation function (DCF) was proposed by [7] to compute the correlation between two group data varying with time. Monte Carlo (MC) simulation was used for model the noise characteristics and our unevenly data as well as to verify robustness of the DCF results. Figure 2 illustrate the single-epoch spectrum (a) and DCF result of significant quasar from 10 quasars (b). Quasar SDSS J081506.93+254124.7 has the lag-time with 125 $\pm$ 20 light-day.

4. $M_{BH}$ estimation

4.1. Velocity dispersion from single-epoch spectrum

$R_{BLR}$ was calculated by DCF, the next step is calculating velocity dispersion ($v$) in order to get the $M_{BH}$. The velocity dispersion estimated by measure the width of broad emission line of single-epoch quasar spectrum (see figure 2 (a)). With redshift range of our sample, MgII is the dominant emission line for measuring. In this work we used IDL Gaussian fitting with 5 parameters to measure the broad emission line and obtain $\sigma$ as a result. To calculate $v$ of BLR, using full width at half-maximum (FWHM) give better result than $\sigma$ [4]. It is found that $\sigma$ has the relation with FWHM as $FWHM \approx 2\sqrt{2\ln 2} \cdot \sigma$. Referring from DCF result, SDSS J081506.93+254124.7 is the one can estimate BLR distance thus $v$ of this quasars is $(3500 \pm 440) \times 10^3 \text{ km s}^{-1}$. Moreover BLR distance and $v$ calculated, there is one crucial factor to estimate the $M_{BH}$ called virial coefficient ($f$). The $f$ is explain the geometry and
kinetic energy of BLR gas which is significant to the uncertainty of BH mass estimation. Studying from many works give a slightly different $f$ for FWHM measurement. Normally, $f$ is scaling from $M_{BH} - \sigma$ relation of low-$z$ AGNs [8]. In this work, we adopted $f$ from other papers wiz (i) $f_{rms} = 1.44 \pm 0.49$; $f_{mean} = 1.17 \pm 0.50$ [9], (ii) $f = 1.51 \pm 0.49$ [10] and (iii) $f = 1.12 \pm 0.32$ [11]. As a result, our $M_{BH}$ calculated have its error including the different of term $f$, $M_{BH} = (4.3 \pm 2.0) \times 10^8 M_\odot$.

5. Discussion and conclusion
There are many ways to estimate the SMBH masses of quasars. However, every method need at least one time spectroscopic observation. Reverberation mapping is the most popular method which have two types, SRM and PRM. Although, the quickly method is single-epoch (SE) virial mass, the empirical of this technique based on SRM results. BLR distance in SE method using R-L relation from low-$z$ AGNs, consequently the uncertainty of $M_{BH}$ estimated quite larger than other method. For example, our quasar SDSS J081506.93+254124.7 estimated $M_{BH}$ from PRM is $(4.3 \pm 2.0) \times 10^8 M_\odot$ while $M_{BH}$ from SE method is $(3.0 \pm 2.1) \times 10^8 M_\odot$. Both methods used the same calculation for velocity dispersion of BLR. Furthermore, the more of observation could gain better result and also the more accuracy of coefficient $f$ estimated.

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