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PROPOSAL OF PHOTOMETRIC REVERBERATION MAPPING WITH BOOTES-4

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RESUMEN

Reverberation mapping(RM) es una técnica poderosa para medir la masa de agujeros negros en núcleos de galaxias actívas (AGNs). Sin embargo los programas de RM clásicos, que utilizan espectroscopía para monitorear las líneas de emisión de la región de lineas anchas (BLR), generalmente están limitados sólo para los agujeros negros supermasivos con telescopios de la clase de 2-m. En años recientes, un avance extraordinario ha sido logrado con la técnica de RM fotométrica, que abre la puerta para medir eficientemente el tamaño del BLR y la luminosidad restada de la galaxia anfitriona, incluso con telescopios pequeños. Considerando la disponibilidad de otros telescopios BOOTES alrededor del mundo, consideramos proponer colaboraciones internacionales como uno de los programas de monitoreo de largo plazo para telescopios robóticos.

ABSTRACT

Reverberation mapping(RM) is a powerful technique to measure the mass of black holes in the active galactic nuclei(AGN). Yet the classical RM programs, which uses spectroscopy to monitor emission lines from the broad line region(BLR), are generally limited only for very supermassive black holes with large 2m-calss telescopes. In recent years, a breakthrough is remarkably achieved with photometric RM technique, which opens the door to efficiently measure the BLR size and host-subtracted AGN luminosity even with small telescopes. Considering the availability of other BOOTES telescopes around the world, we could further consider to propose international collaborations as one of the long-term monitoring programs for small telescopes.

Key Words: galaxies: active

1. INTRODUCTION

A black hole(BH) is a region of space-time from which gravity prevents anything, including light, from escaping. Black holes (BHs) are the key points that provide insight into the foundation and formation of (quantum-) gravity theories. Such objects are usually characterized by three physical properties: mass, angular momentum, and charge. Among these properties the most fundamental is the mass, which characterizes all BHs. 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 (Chelouche et al. 2012). Angular momentum is only relevant for rotating (Kerr) BHs while charge is less studied for astronomical researches because it is beyond the reach of observations. Up to now, a wide range of BH masses are implied through a series of astronomical observations: from solar mass BHs as the end products of massive stars to supermassive BHs (SMBHs) at the centers of galaxies with masses that may easily exceed a million solar masses (Salpeter 1964; Lynden-Bell 1969). Those SMBHs can be easily observed when they accrete large amounts of gas from their surroundings, a situation that causes them to shine at levels of up to a thousand times the energy produced by a large galaxy containing 100 billion stars.

Most if not all galactic nuclei contain supermassive black holes with $M < 10^6$ solar masses. Whether these black holes originate from 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 these properties, it is dif-

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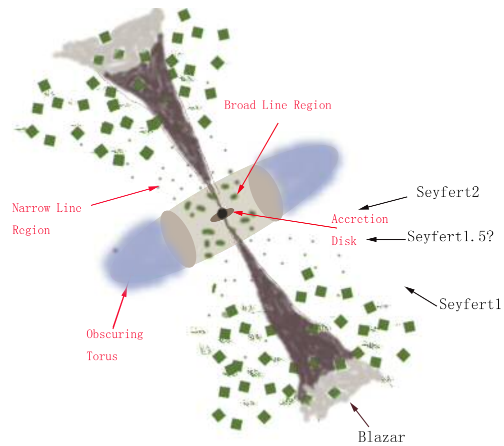

Fig. 1. The Unification Model combines the different types of AGN into one very possible ex-planation based on viewing angle. This model shows the black hole at the center with a nearby accretion disk of fast moving matter. Near the accretion disk is the broad-line region, and the narrow-line region may exist outer.

ficult to know anything about their formation and evolution. Recently, our understanding of the co-evolution between galaxy and black hole (BH) formation has progressed significantly (Wandel 1999; Ferrarese & Merritt 2000; Haring & Rix 2004; Peng et al. 2006; Bennert et al. 2010; Cisternas et al. 2011) with new observations being able to probe the first epoch of quasar activity, and place interesting constraints on the mechanisms responsible for BH growth and galaxy formation(Hughes & Blandford 2003). Obtaining deeper physical insight requires that the BH masses must be determined with fair accuracy in a wide sample of objects including the ones with relatively good coverage of different redshifts.

Reverberation mapping has revolutionized our understanding of active galactic nuclei (AGN) during the past decades. Reverberation mapping, mostly focused on the observations in the degree and nature of the correlation between continuum and emission-line flux variations, now gradually becomes one of the major tools for studying the structures and kinematics of the gas in the broad-line region (BLR) , or even the calculation of black holes in active galactic nuclei. Reverberation mapping was pioneered in the late 1990s and early 2000s (Peterson 2004). This technique assumes the standard model, and that AGNs follow the same relationship between black hole mass and host-galaxy bulge velocity dispersion (Hughes & Blandford 2003).

2. THE BASIC THEORY

The model for AGNs(see fig1), exhibits the black hole usually hosted at the center of a accretion disk

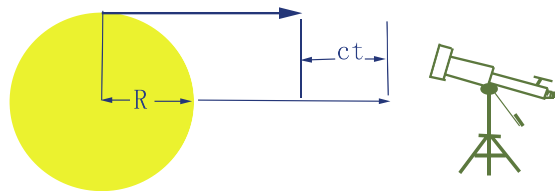

Fig. 2. A spherical object of radius R emits an instantaneous flash of light, which is observed with a time lag τ =R/c. This method gives the radius of the broad-line region, c, used in. The telescope represents the observers line of sight.

with differential moving matter along the disk radius. Near the accretion disk is the broad-line region (BLR), which contains fast moving gases ($v_{FWHM} > 900$ km/s) that cause Doppler broadening in the permitted emission lines, mainly of hydrogen. Previously, AGNs classified on their spectral features, were divided into blazars (variable high energy sources) and Seyferts. The unification model as seen in Fig. 2.1 shows that these sources are likely to be separated with different possible viewing angles.

The time delay of variability between continuum and emission line can be as a probe of the radius of the broad-line region according to the geometrical features (Fig. 2.2). Solving the virial theorem for mass, -2K = U (Carroll & Ostlie 1996), where U is the gravitational potential energy of the gas clouds in the broad-line region,

$$U = -G\frac{M_{BH}m}{r_{BLR}} \tag{1}$$

and K is the kinetic energy, where is the velocity dispersion within the broad-line region.

$$K = \frac{1}{2}m\Delta\nu^2 \tag{2}$$

This yields a virial mass estimate:

$$M_{BH} = f\frac{\Delta\nu^2 c\tau}{G} \tag{3}$$

where f is a scaling factor in the order of unity to account for the geometry of the BLR, Δv is the Doppler broadening velocity, $c\tau(r_{BLR})$ is the radius of the broad-line region as explained in section 1.3 and G is the gravitational constant.

Measuring the mean time lag τ between flux variations of the triggering optical-ultraviolet continuum (from the compact accretion disk around the black hole) and the emission line brightness echo of the BLR gas clouds can be as a criterion to figure out the size of BLR. The BLR size measured by the centroid τ of the cross-correlation of light curves represents a luminosity-weighted average(Penston 1991). Evidences show that the BLR clouds are essentially in virialised motion around the central black hole(Peterson 2004). Combining R_{BLR} with velocity dispersion $\Delta\nu$ of the emission line, the virial black hole mass can be estimated.

Reverberation mapping, in general, relies on the time resolution, and therefore it is vital that the light curves should be sufficiently well sampled. According to Nyquists Theorem, the sampling rate(SR)of the feature of interest, i.e. the lag, must be SR= t_{lag} / $t_{sampling}$ > 2.2. Considering the observational cases, data points are usually lost due to poor weather or technical problems, hence one should aim at SR > 3. So far, however, many BLR sizes have been derived from sparsely sampled light curves (SR < 3) with a limited potential to reach better than 30% accuracy, and it could be too optimistic for undersampled data any quoted uncertainties of 30%.

Most of the previous results of Reverberation Mapping are mainly from light curves between emission line and continuum, and it is still the same today. Because the data requirements are relatively modest, rather than attempt to obtain the velocity-delay map, it is most common to determine the cross-correlation function and obtain the lag (mean response time) through the following formula:

$$\mathrm{CCF(t)} = \int \Psi(\tau) ACF(t-\tau) dz$$

In this formula, The ACF means the autocorrelation function, which is the similarity between observations as a function of the time lag between them. It is a powerful mathematical tool for finding the repeating patterns.

3. THE PAST DECADES ENDEVOR

Reverberation spectra usually require observations with at least a 2 m-class telescope. The BLR sizes range between a few and several hundred light days and the time spans become even longer in the observers frame due to the time dilation factor 1 + z for high-redshift cases. To match distinct echo features, light curves over a few months to several years are needed. Consequently, spectroscopic reverberation mapping is resource expensive and it becomes prohibitive at high redshift.

Reverberation lags have been measured about 50 AGNs, mostly for one or more Balmer lines, but in some cases for multiple lines. About 17 low-luminosity AGNs (Seyfert 1 galaxies) have been successfully monitored and get statistically meaningful results(Wandel, Peterson, & Malkan 1999). Best studied among these is the Seyfert 1 galaxy, NGC 5548, which was monitored from the ground for over 8 years, and from space for several long periods(Peterson et al. 1999). Several other Seyfert 1s were observed for periods of order 1 yr or less, and nine Seyfert 1s galaxies were studied over a period of 8 yr(Peterson et al. 1998a). The measured time lags between the emission lines and the continuum light curves in these objects can be interpreted as the delayed response of a spatially extended BLR to a variable, compact source of ionizing radiation. While the observations do not uniquely determine the geometry of the BLR, they give its typical size for Seyfert 1s galaxies, which is of the order of light-days to several light-weeks (10^{16}-10^{17}cm). Recent studies have shown that the time lags determined in NGC 5548 for different observing seasons correlate with the seasonal luminosity of the object and have presented evidence for Keplerian motions of the BLR gas(Peterson et al. 1999).

The sample consists of 28 PG quasars. Objects with a northern declination, B<16 mag (based on the magnitudes given in (Schmidt et al. 1983), redshift z<0.4, and a bright comparison star within 3.5 of the quasar, were selected. Kaspi (2000) and his group did further observations and presented detailed information about the sample. Those observations were carried out using the Steward Observatory (SO) 2.3 m telescope and the Wise Observatory (WO) 1 m telescope.

Recently, one of the inspiring work, in which they used the robotic 15cm telescope VYSOS-6 on Cerro Armazones, Chile, successfully measured two AGNs' BLR sizes and luminosities(Hass et al. 2011). Thus the photometric reverberation mapping opens the door to efficiently measure hundreds of BLR sizes and host-subtracted AGN luminosities even with small telescopes

We plan to make some tests on the photometric reverberation mapping with BOOTES-4 after adding some new filters and improving the performance of this telescope. If we use the broadband photometric reverberation mapping mode, in which the R and V band filters provide a measurement of time variable emission in Hα and Hβ respectively mixed with an observation of the continuum, then we could put the I-band filter as a tracer of continuum-only measurement. This broadband photometric method might efficiently estimate the black hole mass because we can put a greater weight on statistical analysis and less on spectral data. On the other side, the narrow-band photometric reverberation mapping is a similar method that accesses spectral features by only observing in a wavelength range that barely covers the spectral feature. However, each filter needs to be fit to the galaxy since they have different redshift. Filters are produced for one specific wavelength range, requiring multiple expensive filters for observations of objects with differing redshifts.

4. DISCUSSION AND SUMMARY

The environment surrounding black holes or supermassive black holes in active galaxies can be probed through the reverberation mapping technique. This technique usually requires the galactic nuclei to be simultaneously observed spectroscopically with a large 2m-class telescope and photometrically with a smaller telescope. Though spectroscopic reverberation mapping may be the only way available up to now to probe the details of the innermost AGN structure and the geometry of the BLR, the remarkable advantage of photometric reverberation mapping with suitable filters is to efficiently measure BLR sizes and host-subtracted luminosities for large AGN and quasar samples even with small telescopes. Broadband photometric reverberation mapping covers more wavelength, using filters that are commonly accessible to universities and other organizations. The wavelengths covered are still able to extract the spectral features information as each broadband filter possesses only one dominant spectral feature.

As mentioned above, we could also develop a method using the 0.6-m BOOTES-4 telescope that might allow an accurate estimate of the mass of a supermassive black hole through broadband photometric reverberation mapping. Other methods are available that accurately measure black hole mass, such as spectrophotometric reverberation mapping, velocity outflow in radio and velocity dispersion. But these methods are tedious and expensive to implement. The area of a supermassive black hole and surrounding environment is so small compared to its host galaxy, that it cannot be resolved with any telescope. We plan to make a breakthrough by using the BOOTES-4 telescope with a possible broadband or narrow photometric reverberation mapping technique. Since obtaining large telescope time for long observing campaigns is difficult, we would propose to make full use of those small telescopes available around the world once we get some achievements with BOOTES-4.

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