A New Method to Identify Low-mass SMBHs

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Abstract

Low-mass supermassive black holes($\lesssim 10^6 M_\odot$) in nearby dwarf galaxies can be regarded as remnants of primordial black holes. Therefore, they are of importance in high-redshift BH seed formation, and co-evolution of central massive BHs and their hosts. Also, at the thought of the relations such as $M_{\rm BH} - \sigma_*$, $M_{\rm BH} - M_{\rm bulge}$, and $M_{\rm BH} - L_{\rm bulge}$, how these are like at the low-mass ends is significant interest. Over the last two decades, more and more black holes within this mass range have been studied extensively. However, due to the difficulties of their observation, we do not have enough low-mass BH samples to constrain these relations. Here we will introduce a new way of searching for low-mass BHs using hour-scale optical variability, and our recent observation with Subaru/FOCAS.

1 Introduction

It has been well established by now that almost all massive galaxies ($M_* \gtrsim 10^{10} M_\odot$) host massive black holes (BHs) at the centers. Moreover, BH masses correlate with properties of host galaxies such as stellar velocity dispersion, bulge luminosity, and bulge mass.(Gebhardt et al. 2000; Marconi & Hunt 2003; Gültekin et al. 2009; Kormendy & Ho 2013) These relations are, however, poorly constrained for the lower-mass ends($M_{\rm BH} \lesssim 10^6 M_\odot$). Also, it is still unknown what fraction of low-mass galaxies($M_* \lesssim 10^{10} M_\odot$) have black holes in their centers(occupation fraction). Therefore, it is very important to identify much more low-mass supermassive black holes(SMBHs).

In particular, the low-mass end of scaling relations count much for constraining models of high-redshift BH seed formation. According to Voronteri & Natarajan (2009), in case of BH masses $\lesssim 10^6 M_\odot$, the slope and scatter of $M_{\rm BH} - \sigma_*$ vary depending on whether BH seeds were massive($\sim 10^{4-5} M_\odot$) or Population III like stars($\sim 100 M_\odot$). Also, the occupation fraction is important for models of BH seed formation.(e.g. Volonteri et al. 2008; Miller et al. 2015) Indeed, the BH with its mass of $\sim 10^9 M_\odot$ was found at z $\sim$ 7. However, it is not revealed how seed BHs evolved into such high mass at the early time of the Universe.

At present, dynamical detections of small BHs in distant dwarf galaxies is not impossible, so we must search by using AGNs. Over the last decade, systematic searches using optical spectroscopy from Sloan Digital Sky Survey (SDSS) have found hundreds of low-mass AGN. These studies utilized broad-line width of AGN, calculated the virial BH masses, and identified BHs with their mass below $2 \times 10^6 M_\odot$(Greene & Ho 2004, 2007) More recently, Reines et al.(2013) increased the number of AGN samples in dwarf galaxies by an order of magnitude by using both narrow and broad emission line AGNs of nearby (z$\sim$0.055) dwarf galaxies($M_* \lesssim 3 \times 10^9 M_\odot$). Furthermore, by conducting a multi-wavelength observation like this, the smallest SMBH so far, named RGG 118, was estimated to have mass of $\sim$50,000$M_\odot$ (Baldassare et al. 2015).

The optically-selected samples are, however, biased toward relatively high Eddington ratios, and toward galaxies whose star formation is not ongoing. Lately, the multi-wavelength observation using optical, X-ray, and radio waves have been widely conducted to compensate for the bias. (e.g., Gallo

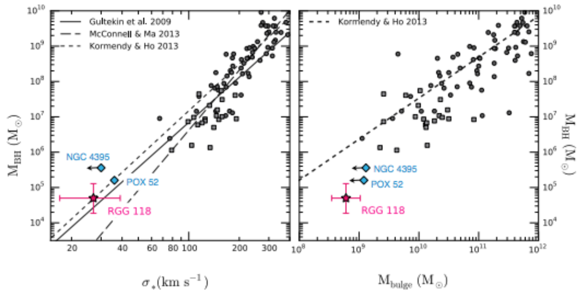

Fig 1: Both: Black solid/dashed lines represent various determinations of scaling relations. Left: $M_{\rm BH}-\sigma_*$ relation Right: Dashed black line gives the $M_{\rm BH}-$ $M_{\rm bulge}$ relation. Baldassare et al. (2015)

et al. 2008, 2010; Reines et al. 2011, 2014; Reines & Deller 2012; Schramm et al. 2013).

Here we present our recent optical spectroscopic observation. The sample is obtained from a prior observation(Tominaga et al.) by using Subaru telescope with the Hyper Suprime Cam (HSC). We used Subaru telescope with the Faint Object Camera and Spectrograph (FOCAS) to determine redshifts and masses of samples.

2 Method

As stated above, the recent research of this region has been improved to some extent by multiwavelength observations. However, there are still some difficulties: (1) the Hα emission line can be no longer used at z $\gtrsim$ 0.35 because of redshift. As the SDSS has this problem, it could not access sources at higher redshift. (2) The very deep search using X-ray, Chandra Deep Field, cost as much as 4 Ms and ended up detecting only 3 favorable AGNs (Schramm et al. 2013). A large survey as deep as this observation using X-ray is nearly impossible to conduct to date. Therefore, we need newer methods to identify farther, smaller BH populations more effectively, and then increase the number of low-mass BH samples.

One possible clue to find SMBHs is using with rapid variability. Due to the small size of the systems, their accretion disks are not stable, and so low-mass SMBHs show rapid variability. As for preceding research, Peterson et al. (2005) states that NGC 4395, the least-luminous Seyfert 1 galaxy, shows hour-scale variability, and also, estimated its mass to be $\sim 3.6 \times 10^5 M_\odot$ by using reverberation mapping.

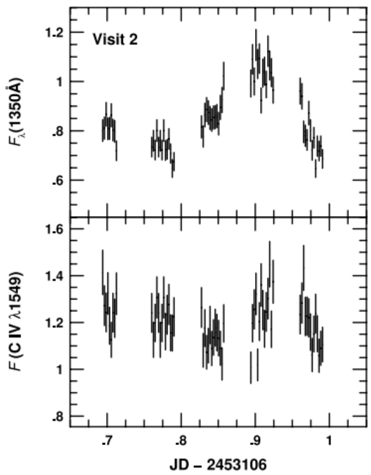

Fig 2: Light curves for the UV continuum at 1350 Å (top) and the C_{IV} λ1549 emission line (bottom). Peterson et al. (2005)

Although Sarajedini et al.(2011) selected AGN candidates at the point of their variabilities, they did not derive thorough constraint to detect small active SMBHs.

Therefore, we started a deeper ($\sim$ -26mag at g- and r- bands), higher (1 hour) - cadence, and wider ($\sim$12 deg^2) observation using the Subaru telescope with FOCAS.

3 Observation

First we conducted the optical imaging observation on July 2014 and May 2015 with Subaru Telescope using HSC(PI: N. Tominaga). As of now, only HSC can perform this deep, wide and high-cadence survey. After rapidly variable sources were found, we selected point-like sources located at the center of the galaxy. These sources show rapid (a few hours to a day) variability, so they could be AGNs with low-mass black hole.

Next, these spectra were taken on June 2015 with Subaru telescope using FOCAS to determine their redshift and the SMBH masses(PI: T. Morokuma). These data are reduced by using IRAF.

4 Discussion

In order to understand BH seed formation and growth in the early universe, observation of nearby dwarf galaxies is thought to be the best way as of now. To date, various method to find and select low-mass SMBHs have been conducted as I mentioned above. Above all, using optically visible rapid variability is more effective at the point that it suffers from less contamination and that it has the ability to expand to high redshift coverage (z$\sim$1). Usually, x-ray observation is annoyed by contamination of Ultra Luminous X-ray source (ULX), but optical observation is less affected by this problem. As stated, the SDSS covers only z $\lesssim$ 0.35, however, if our method is established, this range will be expanded to z $\sim$ 1. Our samples, of course, should be cross-checked with other wave bands to gain a confidence level as future work. To sum up, we aim to not only identify higher-redshift, lower mass SMBHs but also to see that in larger numbers.

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