Intermediate-mass black holes in galactic nuclei

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Abstract. We present the first homogeneous sample of intermediate-mass black hole candidates in active galactic nuclei. Starting with broad-line active nuclei from the Sloan Digital Sky Survey, we use the linewidth-luminosity-mass scaling relation to select a sample of 19 galaxies in the mass range $M_{\rm BH} \approx 8 \times 10^4 - 10^6\, M_\odot$. In contrast to the local active galaxy population, the host galaxies are ~ 1 mag fainter than M^* and thus are probably late-type systems. The active nuclei are also faint, with $M_g \approx -15$ to -18 mag, while the bolometric luminosities are close to the Eddington limit. The spectral properties of the sample are compared to the related class of objects known as narrow-line Seyfert 1 galaxies. We discuss the importance of our sample as observational analogues of primordial black holes, contributors to the integrated signal for future gravitational wave experiments, and as a valuable tool in the calibration of the $M_{\rm BH} - \sigma_\star$ relation.

1. Background & Sample Selection

Dynamical studies have established the existence of supermassive black holes (BHs) with masses $M_{\rm BH} \approx 10^6 - 10^9\, M_\odot$ in the centers of most, if not all, local galaxies with bulges (Magorrian et al. 1998; Richstone 2004). A significant challenge to any model of cosmological BH growth is the nature of seed BHs. Observations of intermediate-mass BHs ($M_{\rm BH} \approx 10^3 - 10^6\, M_\odot$) in the local Universe would provide the most direct empirical constraints on such seeds. Their number and mass distribution will impact the expected integrated background in gravitational radiation (e.g., Hughes 2002). Intermediate-mass BHs have practical value in that they offer tremendous leverage in anchoring local BH-galaxy scaling correlations such as the $M_{\rm BH} - \sigma_\star$ relation.

Recently discovered intermediate-mass BH candidates in galactic nuclei offer tantalizing hints as to the nature of this population. NGC 4395 is a very late-type (Sdm) spiral with no bulge component. Nevertheless, it has the emission properties of a type 1 active galactic nucleus (AGN; Filippenko & Sargent 1989; Filippenko, Ho, & Sargent 1993). Mass estimates based on the Hβ linewidth-luminosity-mass scaling relation and X-ray variability suggest a BH mass of $10^4 - 10^5\, M_\odot$. Interestingly, these agree with the limit of $< 10^5\, M_\odot$ derived from the $M_{\rm BH} - \sigma_\star$ relation (Filippenko & Ho 2003; Tremaine et al. 2002). POX 52, whose optical spectrum is remarkably similar to that of NGC 4395, has a dwarf elliptical host (Barth et al. 2004). The galaxy has a central velocity dispersion of 36 km s^{-1}, which yields a mass estimate of $M_{\rm BH} = 1.4 \times 10^5\, M_\odot$, again consistent with the value of $1.6 \times 10^5\, M_\odot$ derived from the Hβ linewidth-luminosity-mass scaling relation. NGC 4395 and POX 52 fall on the $M_{\rm BH} - \sigma_\star$ relation while their hosts are anomalous compared to the local AGN population (Ho, Filippenko, & Sargent, 1997a, 2003; Kauffmann et al. 2003), which is invariably affiliated with massive, bulge-containing galaxies.
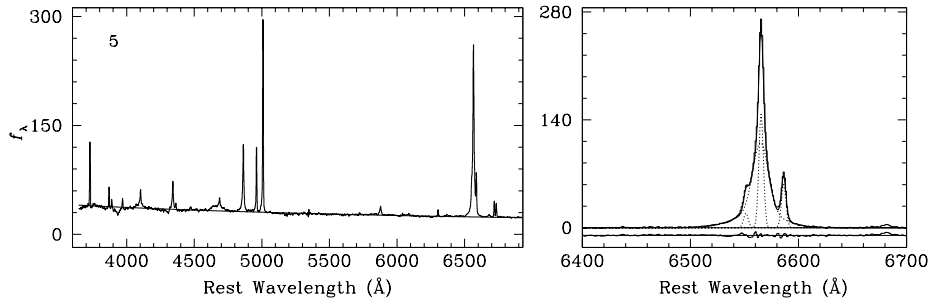
Figure 1. Sample spectrum. *Left:* An example of our power-law fit to the continuum. *Right:* Enlargement of the region around Hα+[N II] λλ6548, 6583. In the upper plot, the data are shown in histogram, the individual models for the narrow and broad lines are shown in dotted lines, and the sum of all the fitted components is shown as a solid line. The lower plot gives the residuals of the fit. The ordinate of the plots are in units of 10^{-17} erg s^{-1} cm^{-2} Å^{-1}.

Unfortunately, it is currently technically impossible to obtain direct mass measurements for $M_{\rm BH} \lesssim 10^6\ M_\odot$, because of our inability to resolve the BH sphere of influence for all but the nearest galaxies in the Local Group (e.g., M33; Gebhardt et al. 2001). Thus, the best hope to find intermediate-mass BHs is through an AGN survey. However, it may be that objects like NGC 4395 are quite rare. To accumulate a significant sample will require a large survey. Also, both the radiative signatures of accretion and the host galaxies themselves will be intrinsically faint. As a result, detection of the faint AGN will be limited by sensitivity and host galaxy contamination.

A large-area, sensitive, and uniform optical spectroscopic galaxy survey, such as the Sloan Digital Sky Survey (SDSS; York et al. 2000), offers the best opportunity for finding a significant number of new intermediate-mass BH candidates. We present our initial sample from the SDSS First Data Release (DR1; Abazajian et al. 2003).

We begin with the 153,000 galaxy and quasar spectra from the DR1. We use the Principal Component Analysis code of Hao (2004) to model and remove contaminating starlight. We then select all broad-line AGN with $z \leqslant 0.35$ based on the presence of broad Hα emission (Ho et al. 1997b). We estimate BH "virial" masses using a variant of the empirically determined linewidth-luminosity-mass scaling relation of Kaspi et al. (2000), which relates $M_{\rm BH} \propto L^{0.7} v^2$, where L is the AGN luminosity at 5100 Å and v is the FWHM of (typically) broad Hβ. To determine v we use the stronger Hα as a surrogate. To properly deconvolve the narrow components of the Hα+[NII] complex we model the [S II] λλ6716, 6731 doublet with a superposition of Gaussian components and then scale this model to fit the complex (Ho et al. 1997b). The continuum luminosity is derived from a power-law fit (see Fig. 1). From the sample of objects with $M_{\rm BH} \leqslant 10^6\ M_\odot$ we remove all objects with a stellar continuum $\gtrsim 20\%$ of the total continuum, due to unreliable Hα FWHM measurements. The final sample of 19 objects has a mass distribution shown in Fig. 2 (for details see Greene & Ho 2004).

2. Properties

Our objects are analogous to the class of AGNs known as narrow-line Seyfert 1s (NLS1), which are thought to possess relatively low-mass BHs emitting at a high fraction of their Eddington rates (e.g., Boroson 2002). By the linewidth criterion, all of the objects would technically qualify as "narrow-line" sources: the broad Hα component has FWHM ranging from 464 to 1730 km s^{-1}. In keeping with expectation the derived Eddington ratios mostly cluster around $L_{\rm bol}/L_{\rm Edd} \approx 1$ (Fig. 2). We caution that these values were derived assuming a single bolometric correction of $L_{\rm bol} = 9.8 L_{5100}$ (McLure & Dunlop
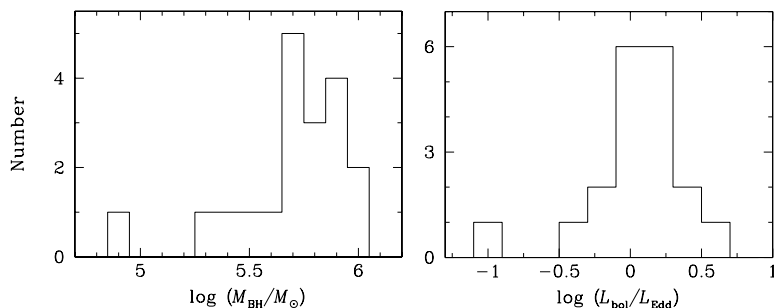
Figure 2. Distribution of virial BH masses (left) and Eddington ratios (right) for our sample.

2004) although the spectral energy distributions of AGNs are known to vary significantly with accretion rate (Pounds et al. 1995; Ho 1999). However, our sample shows a greater diversity of Fe II and [O III] strengths than in previous samples of NLS1s.

The morphology of the host galaxies of intermediate-mass BHs is of fundamental importance for understanding the origin of this class of objects and their relationship to the overall demography of central BHs in galaxies. While we cannot obtain detailed morphology from the SDSS data, the host absolute magnitudes (Fig. 3) are relatively low-luminosity and therefore more likely to be late-type galaxies (c.f. NGC 4395 and POX 52 above). More detailed morphological information requires deep, high-resolution imaging to disentangle a (presumably tiny) bulge component.
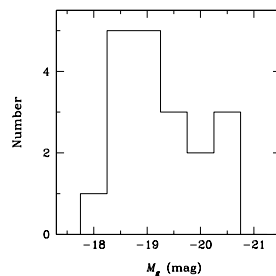
Figure 3. Host galaxy *g*-band absolute magnitudes.

3. Future Work

We employ a simple technique to exploit the breadth of the SDSS galaxy spectroscopy to extend the demography of central BHs at least 1 order of magnitude below the 10^6 $M_\odot$ threshold, a regime hardly explored previously. We hope to use the width of narrow emission lines as a proxy for stellar velocity dispersion (e.g., Nelson & Whittle 1996) to select additional candidates . Preliminary stellar velocity dispersions using the ESI spectrograph at Keck yielded 12 AGNs with $\sigma_\star < 70$ km s^{-1}. As Fig. 4 shows, the objects with velocity dispersions appear to fall on the extrapolation of the local $M_{\rm BH} - \sigma_\star$ relation. The complete data set will test whether the BH mass estimates we derive obey the $M_{\rm BH} - \sigma_\star$ relation and the reliability of the virial mass estimator for AGNs. It would also be valuable to compare the velocity dispersions derived from stars with those derived from gas. High-resolution, deep imaging is needed to quantify the morphologies and detailed structural parameters of the host galaxies. Do these objects have bulges, and if so, what kind and where do they fall on galaxy scaling relations like the fundamental plane? Finally, much work remains to be done, especially at non-optical wavelengths, to further characterize the properties of the AGNs themselves.
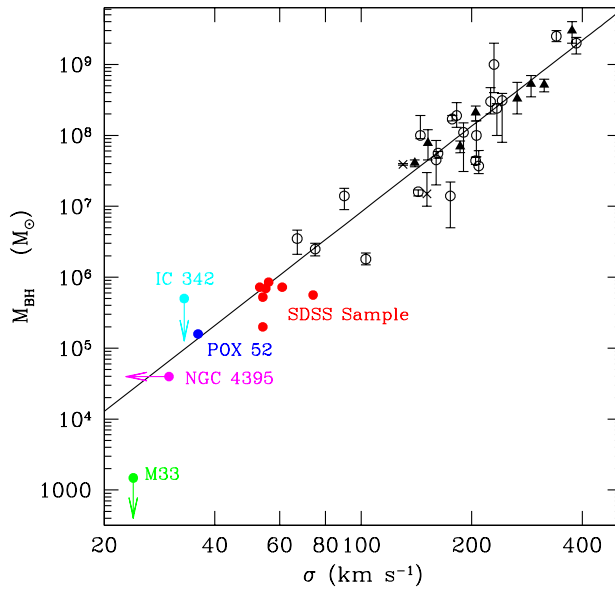
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Figure 4. The $M_{BH} - \sigma_\star$ relation, including objects from our February ESI run. Points with error bars represent nearby galaxies with fundamental measurements of black hole mass from stellar dynamics (open circles), gas dynamics (triangles), or maser dynamics (crosses). Upper limits to the black hole masses in the nearby, inactive galaxies M33 (Gebhardt et al. 2001) and IC 342 (Böker et al 1999) as well as NGC 4395 and POX 52 are shown. This preliminary result suggests our objects are consistent with an extrapolation of the local $M_{BH} - \sigma_\star$ relation.

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