THE GALAXY-BLACK HOLE CONNECTION IN THE LOCAL UNIVERSE

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ABSTRACT

Recent results from large surveys of the local universe show that the galaxy-black hole connection is linked to host morphology at a fundamental level and that there are two fundamentally different modes of black hole growth. The fraction of early-type galaxies with actively growing black holes, and therefore the AGN duty cycle, declines significantly with increasing black hole mass. Late-type galaxies exhibit the opposite trend: the fraction of actively growing black holes increases with black hole mass. Issues of AGN selection bias and prospects for near-future efforts with high redshift data are discussed.

key words: galaxies: interactions; galaxies: evolution; galaxies: formation galaxies: Seyfert; galaxies: active

1. INTRODUCTION

The co-evolution of galaxies and their central black holes via feedback mechanisms seems to be an essential ingredient in any comprehensive picture of galaxy formation, but the nature of this symbiotic relationship remains poorly understood. Cosmological simulations of galaxy formation are unable to reproduce observed galaxy properties and population statistics without resorting to some additional heating mechanism (Benson et al., 2003; Bower et al., 2006; Croton et al., 2006; Somerville et al., 2008) which is now routinely identified as the energy liberated by growing supermassive black holes at the centers of galaxies, either in the form of highly efficient (high Eddington ratio) quasar phases, or in a low-level accretion radio mode. It should be noted that alternatives to black hole feedback have been proposed (e.g. Dekel & Birnboim, 2006; Khochfar & Ostriker, 2008). Co-evolution scenarios are also being invoked to explain the observed scaling relations between galaxy bulge mass and black hole mass (Magorrian et al., 1998; Gebhardt et al., 2000; Ferrarese & Merritt, 2000), though again, explanations have been proposed that naturally account for these relations without resorting to feedback mechanisms (e.g. Peng, 2007; Jahnke & Maccio, 2010).

In order to observationally study the galaxy-black hole connection, we require high-quality samples of both normal galaxies and galaxies with accreting black holes (active galactic nuclei; AGN). There are two challenges in creating such samples: (1) we require an AGN selection method that is as unbiased as possible, and (2) we require samples large enough to sub-divide both normal galaxies and AGN host galaxies into potentially relevant populations. There is no reason to expect that the galaxy-black hole connection is the same in all galaxy populations; in fact, recent work shows that this is not the case.

2. CHALLENGES IN QUANTIFYING BLACK HOLE GROWTH ACTIVITY

The ideal population for studying both galaxies and AGN are obscured (Type 2) AGN where material in the nucleus obscures our line of sight towards the cen-
tral engine where the accretion disk and surroundings emit from the X-ray to the radio part of the spectrum. Optical spectra of galaxies with Type 2 AGN are for the most part unaffected by continuum emission from the AGN and so we are able to study the stellar populations and ionized gas. At the same time, we can use wavelengths where AGN emission remains prominent (in X-rays and, sometimes, the mid-infrared) to quantify the nuclear activity of the same system and thus consider the galaxy and the black hole as a single ecosystem that may, or may not be, evolving jointly.

A major challenge in studying the galaxy-black hole connection is the reliable detection of AGN and understanding the biases affecting each selection method. There are several selection techniques available, all of which have practical and theoretical challenges. As mentioned, Type 2 AGN are the ideal sample to study co-evolution, but before we select them, we must assume that the obscuration is an orientation effect (Antonucci, 1993; Urry & Padovani, 1995) and therefore the unobsured AGN do not represent a systematically different population.

The main problem in reliable AGN selection is that at moderate and low luminosities, the signatures of black hole accretion can be overwhelmed by star formation and other processes. The least biased selection method are hard X-ray surveys ($E > 10$ keV) where photoelectric absorption is minimal, but surveys are shallow or are limited in area (e.g. Tueller et al., 2008; Treister et al., 2009b). Selection in the mid-infrared, e.g. using Spitzer IRAC colors (Lacy et al., 2004; Stern et al., 2005) has proved to be unreliable (Donley et al., 2007; Cardamone et al., 2008).

The most efficient selection technique available in the local universe remains selection via emission line diagrams (Baldwin et al., 1981;Veilleux & Osterbrock, 1987) where emission line ratios are used to identify the main source of ionizing photons impacting the interstellar medium. The high-quality spectra obtained by the Sloan Digital Sky Survey (SDSS; York et al., 2000) make it possible to search for AGN in almost $10^6$ spectra and have enabled several key studies on the properties of AGN host galaxies (Kauffmann et al., 2003; Kewley et al., 2006; Schawinski et al., 2007). The interpretation of weak lines and emission lines produced by multiple sources (e.g. star formation, shocks and AGN) however can be ambiguous and thus can be a major source of bias in studies of emission line-selected AGN host galaxies. In particular, the nature of objects in the LINER (low ionization nuclear emission region) has been revisited recently (Stasińska et al., 2008; Sarzi et al., 2010). LINERs make up a large part of the weak emission line population, mostly residing in massive red sequence galaxies. Taken to be powered by AGN, LINERs have been interpreted as the low-Eddington tail of black hole accretion in the local universe (Kewley et al., 2006; Kauffmann & Heckman, 2009). The recent integral field unit study of nearby early-type galaxies by Sarzi et al. (2010) has shown that the LINER-like emission in these objects is extended in nature and is most likely powered by evolved stellar populations such as pAGB (post-Asymtotic Giant Branch) stars, and not by AGN. This re-classification of the bulk of LINERs from AGN to non-AGN has significantly changed our view of the “typical” AGN host galaxy in the local universe.

3. TWO MODES OF CO-EVOLUTION

A detailed look at AGN host galaxies in the local universe reveals several striking features that have implications for our understanding of the galaxy-black hole connection. Dividing both AGN host galaxies and normal galaxies by morphology shows that there are two separate classes of AGN host galaxies in early- and late-type galaxies (see Figure 1). To be more precise, early-type AGN host galaxies form a very particular sub-population of late-type galaxies as a whole, and the same is true of late-types. The division into two separate black hole growth modes in early- and late-type galaxies is further highlighted in Figure 2. The AGN fraction is a strong function of black hole mass, with opposite trends in early- and late-types.

3.1. Black Hole Growth in Early-type Galaxies

In the early-type galaxy population, it is preferentially low-mass ($\sim 10^9 M_\odot$) objects with intermediate (or “green valley”) host galaxy colors that host AGN. They cluster at the low mass end of the red sequence which overlaps with the blue cloud. A detailed analysis of their stellar populations shows that these are post-starburst objects migrating from the blue cloud to the low-mass end of the red sequence following a merger (Schawinski et al., 2007, 2010a). The galaxies thus driven from the blue cloud to the red sequence continue to build up the low-mass end of the red sequence. This mode of black hole growth, associated with quench-
1. The distribution of the fraction of galaxies that host AGN on the color-mass diagram. The contours represent the normal galaxy population while the green shaded contours trace the AGN fraction. In the top-left panel, we show the entire galaxy population, while in the following panels, we show only normal galaxies and AGN host galaxies with specific morphology. The AGN fraction in a specific sub-population (e.g., early-type galaxies of a certain color and stellar mass) is a proxy for the duty cycle of AGN in that population. This figure thus reveals which galaxy populations have a high AGN duty cycle and illustrates the importance of morphology for understanding the role of black hole growth in galaxy evolution (figure from Schawinski et al., 2010b).

3.2. Black Hole Growth in Late-Type Galaxies

The late-type galaxy population presents a different picture. While late-type AGN host galaxies also feature intermediate or green host galaxy colors, they are significantly more massive ($\sim 10^{10} M_\odot$) than early-type host galaxies. The difference in the mass is not due to larger bulges; in fact, early- and late-type AGN hosts have comparable median black hole masses. The additional mass is in a large stellar disk which is likely stable and long-lived. Together with a lack of post-starburst spectral features this suggests that the role of black hole growth in late-type galaxies is fundamentally different from early-types, and that it is not associated with significant merger-driven quenching events. Possible alternative mechanisms fueling the black holes of massive late-type galaxies include secular evolution, perhaps driven by bars (Hasan et al., 1993; Kormendy...
Fig 2.— Which black holes in the local universe are growing? The answer depends strongly on host galaxy morphology. We show the fraction of galaxies that host AGN luminous AGN selected by emission line diagrams as a function of the host black hole mass measured via the $M_{BH} - \sigma$ relation (Ferrarese & Merritt, 2000; Gebhardt et al., 2000; Tremaine et al., 2002). The fraction of early-type galaxies with actively growing black holes, and therefore the AGN duty cycle, declines significantly with increasing black hole mass. Late-type galaxies exhibit the opposite trend: the fraction of actively growing black holes increases with black hole mass over the same range before possibly dropping at the highest black hole masses (figure from Schawinski et al., 2010b).

4. OUTLOOK FOR OBSERVATIONAL EFFORTS AT HIGH REDSHIFT

It should be noted that the division into two modes of black hole growth in early- and late-types is apparent in the local ($z \sim 0.05$) universe and it is not clear to what degree it reflects the state of the galaxy-black hole connection at high redshift. The peak of both star formation and black hole growth occurs in the early universe around $z \sim 2$ (e.g. Ueda et al., 2003; Heavens et al., 2004; Richards et al., 2006; Pérez-González et al., 2008). Data on this epoch remains limited but is set to increase significantly over the next few years as near-infrared facilities become available.

Near-infrared imaging with the new Wide Field Camera 3 (WFC3) onboard the Hubble Space Telescope (Windhorst et al., 2010) will provide a detailed view on the morphology of AGN host galaxies at $z \sim 2$, but spectroscopic data comparable to that of SDSS will be difficult to achieve for anything but the smallest samples. The imaging quality of WFC3 has already yielded intriguing results on the structure of high redshift galaxies, in particular the increasing compactness of galaxies in the early universe (e.g. Ryan et al., 2010; Szomoru et al., 2010).

Obtaining complete samples of AGN at high redshift is also challenging due to the increasing prominence of highly-obscured AGN that may not be individually detected even in the deepest available X-ray data from Chandra (Fiore et al., 2009; Treister et al., 2009a, 2010). The k-correction in X-rays also poses new problems. While the k-correction moves harder X-rays into the observable range of Chandra and XMM-Newton of $2 - 10$ keV, the loss of the softer X-rays makes it more difficult to constrain the obscuring column $N_H$ in high redshift sources.

As these challenges are overcome with new methods and facilities, we will be able to build a complete picture of the galaxy-black hole connection during the crucial epoch of peak activity and growth and push out towards the very young epoch when the first galaxies and black holes formed. Whether the picture we have from the local universe remains relevant to the early universe remains to be seen.

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