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Black hole–galaxy co-evolution paradigm: Lessons from narrow line Seyfert 1 galaxies

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The current paradigm of black hole–galaxy coevolution emerged from both the observational advances in the past ten years and the theoretical models of galaxy formation. Several recent results, however, question the standard paradigm of merger driven co-evolution. We briefly review these results, elaborating on lessons learned from the studies of narrow line Seyfert 1 galaxies. We present HST/ACS observations of ten galaxies which host narrow line Seyfert 1 (NLS1) nuclei, believed to contain relatively smaller mass black holes accreting at high Eddington ratio. At least five galaxies can be classified as having pseudobulges. All ten galaxies lie below the $M_{\rm BH}$ –L$_{bulge}$ relation, confirming earlier results. Their locus is similar to that occupied by pseudobulges. We conclude that the $M_{\rm BH}$ $-\sigma$ and $M_{\rm BH}$ $-L_{bulge}$ are not universal and that the BH growth in NLS1s is governed by secular processes, rather than by mergers. Active galaxies in pseudobulges point to this alternative track of black hole–galaxy co-evolution. Because of the intrinsic scatter in black hole mass–bulge properties scaling relations caused by a combination of factors such as the galaxy morphology, orientation, and evolution, we caution against using the scaling relations to determine BH masses or the geometry of the broad emission line region in AGNs.

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1. Introduction.

The current paradigm of black hole–galaxy coevolution emerged from both the observational advances in the past ten years and the theoretical models of cosmological structure formation. The mass of the supermassive black holes (BHs) in centers of galaxies was found to be correlated with the bulge luminosity of host galaxies (Magorrian et al. 1998; revised in Gültekin et al. 2009). Even a tighter correlation was later found between the BH mass and the velocity dispersion (σ) of the bulge (Gebhardt et al. 2000a, Ferrarese & Merritt 2000, Merritt & Ferrarese 2001). Basically, the mass of the black hole seems to be correlated with the mass of the bulge (Häring & Rix 2004). Interestingly, the above relation for normal galaxies also extends to active galaxies (e.g. McLure & Dunlop 2002, Woo & Urry 2002).

The above two results were interpreted to imply that the formation and growth of the nuclear black hole and the bulge in a galaxy are intimately related, and several theoretical models have attempted to explain the observed $M_{\rm BH} - \sigma$ and $M_{\rm BH}$ –L_{Bulge} relations (e.g. Adams et al. 2001, Di Matteo et al. 2003). The hydrodynamic cosmological simulations, such as in Hopkins et al. (2006), naturally account for BH–galaxy co-formation and coevolution by invoking quasar feedback. In this scenario, BHs and galaxies grow through mergers; the resulting gas inflow leads to accretion onto BHs and also triggers star formation; this leads to BH growth and quasars emerge; quasar feedback quenches star-formation; eventually quasars die and we are left with inactive BHs in centers of elliptical galaxies. Recent developments, however, question all aspects of the current paradigm, and here we list some of them. (1) The correlation between $M_{\rm BH}$ and σ is found to be not as tight as previously thought (Gültekin et al. 2009; Graham et al. 2010). (2) We found significant outliers to the $M_{\rm BH}$ –bulge relations (Mathur et al. 2001; 2011). (3) Supermassive BHs exist in centers of bulge-less galaxies (Shields et al. 2008; Satyapal et al. 2007, 2009, Ghosh et al. 2008). (4) Theoretical models require AGN feedback to be at least 5% of the AGN luminosity (e.g. Scannapieco & Oh 2004). While the feedback powered by radio jets can be effective (e.g. Rafferty et al. 2006), only a small fraction of AGNs have strong radio jets. Outflows are ubiquitous in AGNs, but the energy in outflows is observed to be several orders of magnitude below what is required for effective feedback in Seyfert galaxies (e.g. Krongold et al. 2007; Crenshaw et al. 2009). (5) While the correlation between AGN luminosity and star formation rate at high redshift (e.g. Netzer et al. 2009) supports the current paradigm, new observations with *Herschel* show this to be a selection effect; the correlation disappears when lower luminosity AGNs are included (Shao et al. 2010). We found a similar lack of correlation in the low-redshift sample of SINGS galaxies (Grier et al. 2011). (6) Galaxies with pseudobulges are found to host AGNs, so have supermassive BHs in their nuclei (§3).

Of the six results against the standard paradigm listed above, two (2 & 6) are the lessons learned from the studies of narrow line Seyfert 1 galaxies, so I elaborate on these below.

2. The location of NLS1s on the $M_{\rm BH}$ –bulge relations

Soon after the discovery of the tight correlation between $M_{\rm BH}$ and bulge luminosity and between $M_{\rm BH}$ and bulge velocity dispersion, we investigated the location of NLS1s on the $M_{\rm BH}$ –L_{bulge} plane. The rational was as follows. Given that NLS1s have relatively smaller mass BHs, they are perhaps still growing, so may not follow the same correlation as BLS1s or inactive BHs. We estimated BH masses for a sample of AGNs using accretion disk model fits to their spectral energy distributions (SEDs). Bulge luminosities were estimated using observed V-band magnitudes and assuming standard B/T ratios. We found that the NLS1 galaxies lie below the $M_{\rm BH}$ –L_{bulge} relation of inactive BHs (Mathur et al. 2001).

We expanded upon the above result by comparing the loci of BLS1s and NLS1s from a complete sample of soft X-ray selected AGNs (Grupe & Mathur 2004). In this paper the BH masses were estimated using the width of the Hβ line, the optical continuum luminosity and their scaling relations. The width of the narrow [OIII] line was used as a surrogate to estimate the bulge velocity dispersion. We found that the BLS1s and NLS1s occupy two distinct regions on the $M_{\rm BH}$ –σ plane. The two populations are clearly different and the result is robust, and not due to selection effects (Mathur & Grupe 2005a,b; Watson et al. 2007).

The above results had several important implications. First of all they showed that the $M_{\rm BH}$ –σ or $M_{\rm BH}$ –L_{bulge} relations are not universal. At face value, they suggested that the BHs in NLS1s are undermassive for their bulges. This rules out models of $M_{\rm BH}$ –σ relation in which the BH mass was a constant fraction of bulge mass at all times. These results, therefore, met with a lot of skepticism, with claims that either BH masses or the use of [OIII] as a surrogate for σ must be wrong. Note, however, that we had estimated BH masses using completely different techniques in Mathur et al. (2001) and in Grupe & Mathur (2004). Using power density spectra from AGN variability studies, Nikolajuk et al (2009) obtained a similar result independently. It is therefore unlikely that BH masses were underestimated with three independent techniques. Similarly, in Mathur et al (2001), $M_{\rm BH}$ was compared to bulge luminosity, and no [OIII] surrogate was used. Nonetheless, the controversy persisted for almost a decade.

3. HST observations of NLS1s

In order to put the above controversy to rest, we observed a sample of 10 NLS1s with HST ACS. All the targets appeared to be off the $M_{\rm BH}$ –σ relation in Grupe & Mathur (2004). With the high resolution HST images, our hope was to measure the bulge luminosity accurately and so determine the location of these objects on the $M_{\rm BH}$ –L_{bulge} relation. Secondly, using the fundamental plane relation we could also place our sources on the $M_{\rm BH}$ –σ plane.

Figure 1 shows the bulge–disk decomposition of HST images of our sample. The bulge and disk surface brightness distributions were fit using Sersic profiles; for the disk the Sersic index was fixed at $n = 1$ corresponding to an exponential profile. As shows in fig. 1, the fitted profiles reproduced the data well. The bulge luminosities were then calculated by integrating the observed profiles. In fig. 2 we show the $M_{\rm BH}$ –L_{bulge} relation for our sample; indeed, the NLS1s in our sample lie below the standard relation of inactive galaxies (Mathur et al. 2011).

The HST observations led to another result which was unexpected. We found that at least five of our ten targets had $n \lesssim 2$, indicating that they are pseudobulges. The surface brightness of "classical" bulges (and elliptical galaxies) follow the $r^{1/4}$ de Vaucouleurs law. Defined in terms of the Sérsic index n, classical bulges have $n = 4$. The pseudobulges, on the other hand, have more "disky" profiles, with $n \lesssim 2$ (see the review by Kormendy & Kennicutt 2004 (KK04)).

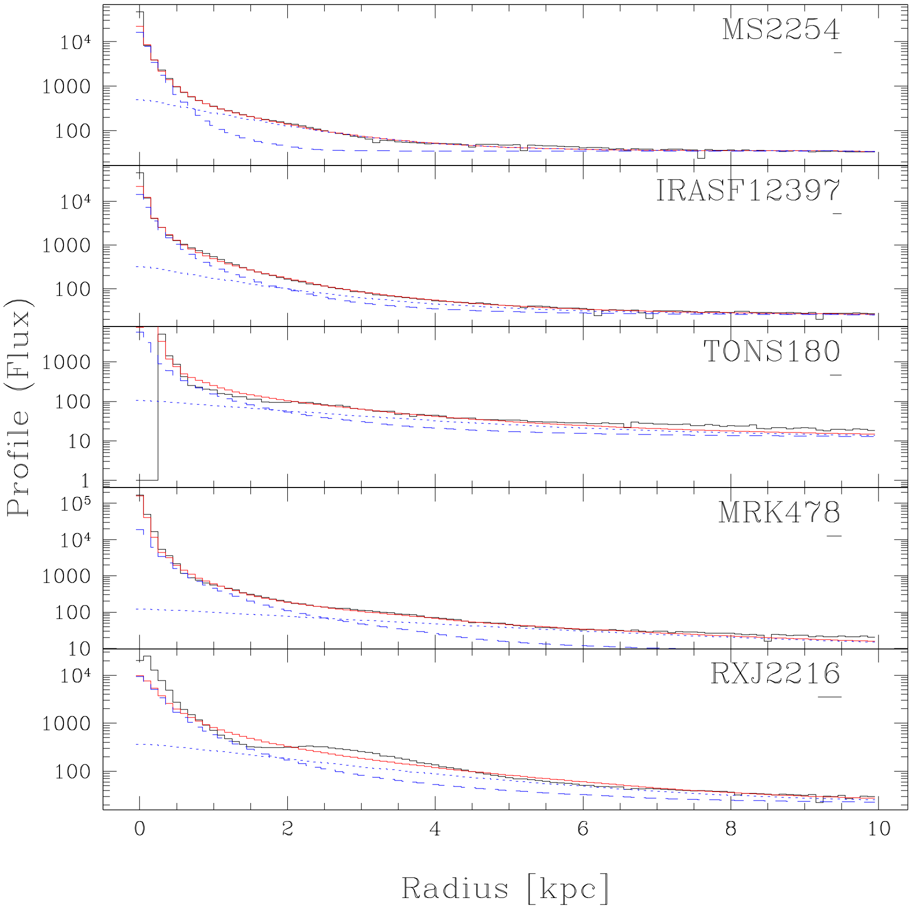

Figure 1: Radial profiles of some of our sample galaxies. The dotted blue line shows the disk component, while the dashed blue line shows the bulge component and the solid red line is the sum of the two (the sky is included in all). The black line is the data. The short horizontal bar on the upper right corner (below the galaxy name) shows the size of the PSF core (5 pixels). This shows that the galaxies are well sampled and are well fit by the bulge+disk profile.

Hu (2008) and Gadotti & Kauffmann (2009) showed that BHs in pseudobulges do not follow the $M_{\rm BH}-\sigma$ relation of normal galaxies. Kormendy et al. (2011) came to the same conclusion using a sample of galaxies with dynamical measurements of BH masses. Our above results are consistent with these: host galaxies of NLS1s have pseudobulges and their BH masses lie below the $M_{\rm BH}-L_{bulge}$ relation. Pseudobulges, however, do not follow the fundamental plane elliptical galaxies and classical bulges (Gadotti 2009); as such we could not determine σ for our sources and so could not place them on the $M_{\rm BH}-\sigma$ relation.

4. Discussion and Conclusions.

The black holes in NLS1 galaxies are truly undermassive for their bulges. If they are growing at a close-to-Eddington rate, they may reach the scaling relations of BLS1s eventually (Mathur

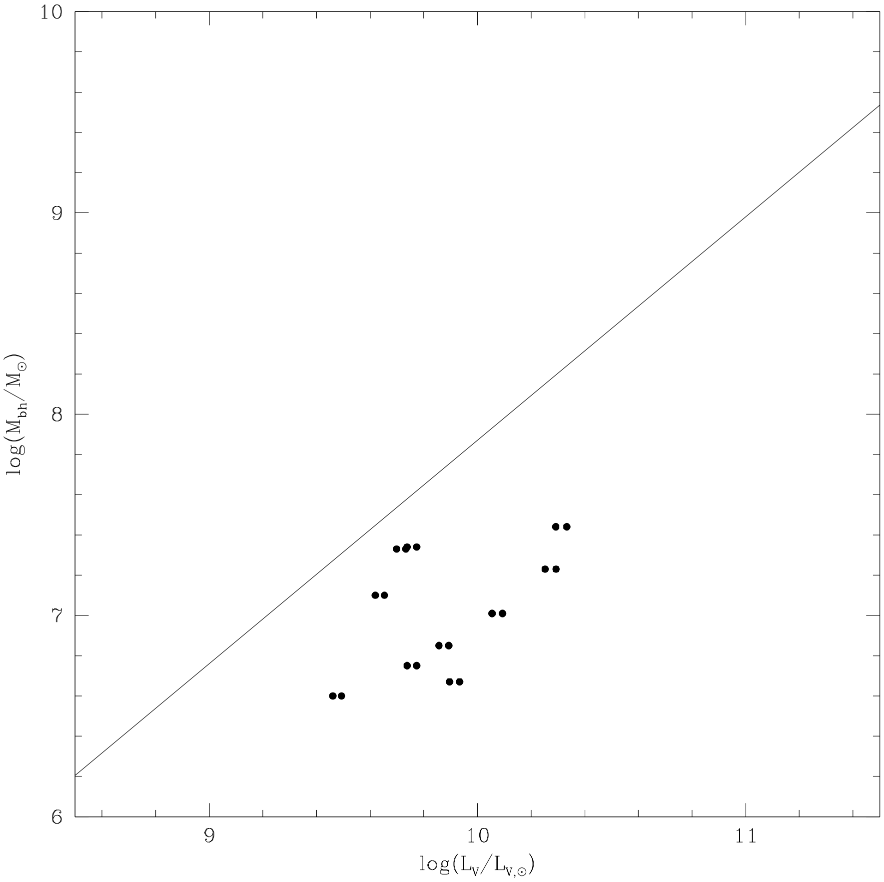

Figure 2: The black hole mass vs. the host bulge luminosity for our sample of NLS1s. For each galaxy there are two points joined by a bar corresponding to two different assumptions about the color corrections. The line is the black hole mass-bulge luminosity relation from Gültekin et al. 2009. It is clear that our sample galaxies do not follow the Gültekin et al, relation, but lie below that relation. The measurement error on $\log L_V/L_\odot$ is smaller than the color correction shown. The error on black hole masses estimates from single epoch spectra is generally believed to be about 0.3 dex.

2000), provided they continue to accrete at the present rate. On the other hand, they may never reach the BLS1 scaling relations, especially if their BHs are growing slowly (Orban de Xivry et al 2011).

Our results clearly show that the $M_{\rm BH}-\sigma$ or $M_{\rm BH}-L_{bulge}$ relations are not universal; they have considerable scatter and offsets (see also Batcheldor 2010). We therefore caution against using these relations to determine BH masses in galaxies in which direct measurements cannot be made. Similarly, these relations should not be used to estimate the geometric correction factors in BH mass estimated using single epoch spectra.

While the elliptical galaxies and classical bulges are products of merging galaxies in the hierarchical galaxy formation scenario, the pseudobulges are believed to have formed through secular processes such as disk instabilities. The triggering of AGN activity and BH growth in pseudobulges cannot be merger-driven. The presence of AGNs in galaxies hosting pseudobulges points to an alternative track of BH–galaxy co-evolution. It should also be noted that this alternative mode of black hole growth is perhaps a dominant one at the present epoch. Weinzirl et al (2009) have shown that about 70–75% of high-mass spirals contain pseudobulges, based on the values of Sersic index or the B/T ratio; Fisher & Drory (2011) have also come to similar conclusion. Given that spirals outnumber ellipticals, it follows that the growth of black holes in most galaxies follows the alternative, secular track at he present epoch.

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