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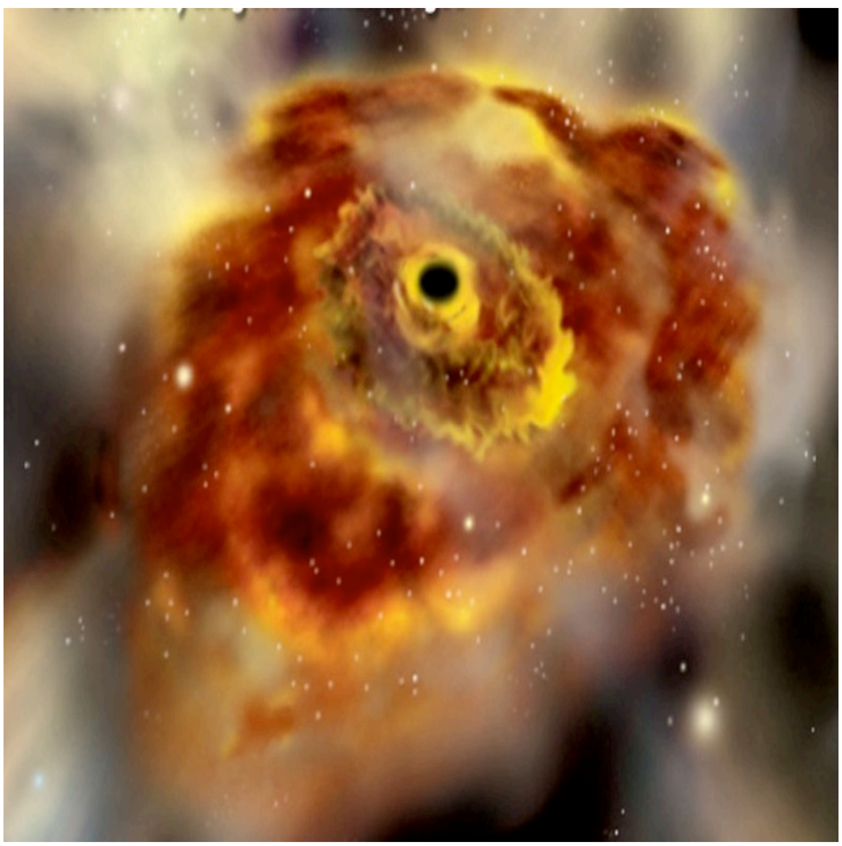
Tracing the Mass Buildup of Supermassive Black Holes and their Host Galaxies

Anton M. Koekemoer (STScI)

Dan Batcheldor (RIT)

Marc Postman (STScI)

Rachel Somerville (STScI)



Artist's conception of a black hole surrounded by dense infalling material

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Tracing the Mass Buildup of Supermassive Black Holes and their Host Galaxies

Abstract

The evolution of the masses of central supermassive black holes (SMBHs) and that of their host galaxies is believed to be fundamental to the overall evolution of both. The strong relationships observed locally between SMBH mass and galaxy bulge mass, together with other phenomena such as outflows, central starbursts and environmental factors, imply a tight physical connection between the processes governing SMBH growth and galaxy evolution. Directly tracing the change in the mass of the central SMBHs with time is thus essential to formulating a complete theory of galaxy formation. However, the observational constraints on these processes become rapidly less certain with increasing redshift, *particularly for the most fundamental observable property of black holes – their mass.* Robust mass measurements have only been directly obtained for limited samples of relatively nearby SMBHs and galaxies, primarily because of limitations on spatial resolution and sensitivity of existing observational facilities. At higher redshift ($z > 0.1$), SMBH masses are derived using **indirect proxies** such as the X-ray luminosity of gas accreting onto the SMBH, the infrared luminosity of obscuring dust, or radio luminosity. These indirect tracers of SMBH mass rely on local calibrations, as well as assumptions about accretion efficiency and dust properties, that are then extended from local samples to those at high redshift. Ideally, the SMBH mass should be directly measured by means of dynamical or reverberation mapping techniques up to high redshift. Direct mass measurements would provide a far more accurate determination of several aspects of the physics of SMBH formation and evolution, such as the change in accretion efficiency with cosmic time. In order to extend local SMBH and galaxy mass measurement techniques to high redshift for sufficiently large samples revolutionary advances are needed in spatial resolution and sensitivity. This paper outlines the considerations for the observational capabilities that would be required during the coming decade, and beyond, in order to directly trace the mass buildup of SMBHs and their host galaxies over cosmic time.

1. Introduction

It is now well known that, in the local universe, all or most galaxies contain a central SMBH, typically with masses in the range $\sim 10^7 - 10^9$ $M_\odot$ (Kormendy & Richstone 1995), and that the SMBH properties correlate with those of the host galaxies. The most fundamental of these correlations is the M_{BH}-σ relation, the empirical observational result that the SMBH mass scales with that of the host galaxy bulge luminosity and mass (Magorrian et al. 1998, Ferrarese & Merritt 2000, Gebhardt et al. 2000, Marconi & Hunt 2003). This relationship strongly suggests a common mechanism underlying their growth and evolution. Recent studies have shown that the SMBH-galaxy scaling relationships change at low mass, suggesting a dependence on galaxy structure (Greene, Ho & Barth 2008), as well as tantalizing evidence for the evolution of the relationships with redshift (Treu et al. 2007). Developing an understanding of the astrophysical origins of these relations is a primary challenge for cosmological models, and is crucial for understanding the role of feedback in suppressing star formation and determining galaxy growth and evolution.

Although the mass of both the central SMBH and its host galaxy are essential for fully adressing these questions, direct dynamical mass measurements have been obtained to date only for a limited number of objects in the local ($z < 0.1$) universe. In addition, probing the kinematics and ionization state of the disks of accreting gas in the central regions around SMBHs is essential because it represents the closest gas to the central black hole, thus directly tracing the energetics of the central engine. The central accretion disks can extend up to several thousand Schwarzschild radii corresponding to a few hundred parsecs for the most luminous AGN. Yet these accretion disks are currently among the least understood of all the phenomena associated with SMBHs in normal galaxies as well as in active galactic nuclei (AGN) as they are barely resolved for just a handful of nearby AGN in the local universe, and remain completely unresolved for all other AGN up to cosmological distances. Obtaining the morphologies and dynamics of these disks not only for local objects, but also for sources at cosmological distances, will provide an unprecedented breakthrough in our understanding of the physics of the central regions immediately around the SMBHs.

2. Obtaining a Census of Black Hole and Galaxy Mass

2.1 Dynamical Measurements of Line-Emitting Gas around the SMBH

The most direct way to measure the mass of a SMBH is by means of emission-line spectroscopy of material within its gravitational radius of influence. For the black hole at the center of our own galaxy this has been achieved by mapping stellar orbits (out to what distance from center?), however, this technique cannot presently be applied to any other galaxy. For galaxies with more massive black holes, the radius of influence can extend up to a few hundred parsecs, enabling a direct measurement of the black hole mass from spectroscopic observations of the central gas (e.g., the black hole in M87, Ford et al 1994).

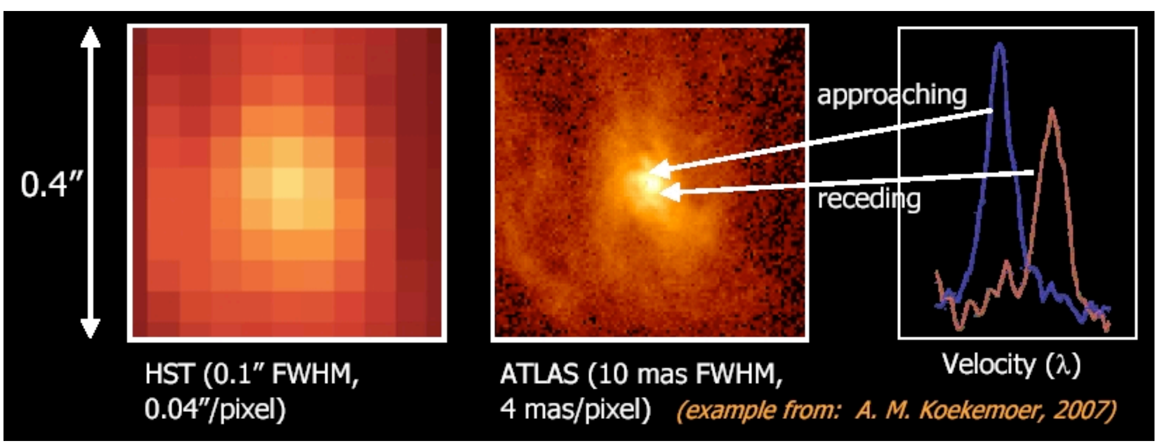

Fig. 1. An example of a nuclear disk of radius 190 parsecs (0.03" at z~5), based on the results that were initially obtained for M87 (Ford et al. 1994), extrapolated to how a similar object would appear at $z \sim 5$. (Left) Appearance of the disk with HST; (Middle) Appearance of the disk with with a telescope with ~10mas PSF (eg ~10-16m diffraction-limited optical/UV telescope in space); (Right) spectra of gas approaching and receding in the central few hundred parsecs, enabling a direct dynamical measurement of the black hole mass.

The central accretion disks subtend only a few tenths of an arcsecond even at distances of only a few Mpc, and their projected angular sizes decrease rapidly below 0.1” beyond redshifts of a few tenths, thereby necessitating the use of indirect mass estimates. A factor of 10 increase in the angular resolution available in the optical/NIR regime would enable such disks to be resolved to out to at least z~0.5-1, and probably to higher redshifts as well, since the angular diameter scale (kpc/”) changes by no more than ~30% from z~0.5 to z~5. Surface brightness diming then becomes the most limiting effect on how far out in redshift one can make such an observation

An example of the observational parameter space probed by direct dynamical mass measurements as a function of distance is shown in Figure 2 (Batcheldor 2008). To accurately model the mass of a SMBH, we are required to resolve the its sphere of influence, $r_h = GM/\sigma^2$, where M is the mass of the black hole and σ is the stellar velocity dispersion (Peebles 1972). Assuming all SMBHs follow the relationship between M and σ, we can plot r_h within the M-σ plane. In addition, we can determine the ability of a diffraction-limited telescope to resolve r_h at a specific distance and wavelength. The optimal spectral features to measure can be determined from the relevant gas and stellar dynamical models. In the optical these are 5200Å (Mgb), 6563Å (H alpha) and 8500Å (CaT). In Figure 2 we show the ability of HST as well as a hypothetical 16m diffraction-limited telescope to resolve r_h given several key distances. It can be seen that with HST, even very massive black holes (above ~10^9 $M_\odot$) can only be measured up to ~160Mpc. On the other hand, increasing the resolution from ~0.1” to ~0.01” can not only enable the mass measurement of such systems to ~1 Gpc (z ~ 0.5) but also therefore up to much higher redshifts, since the angular size scale changes very slowly above this redshift with current cosmological parameters (with H_0=71, $omega_M$=0.27, and $omega_{vac}$=0.73, at z=0.5, 1, 5, the angular scales corresponding to 0.01” are 60, 80, and 65 pc respectively).

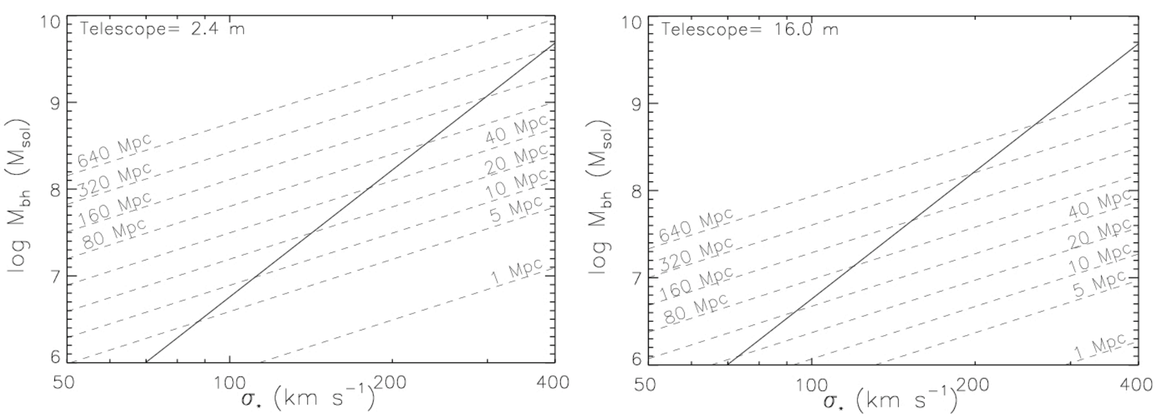

Figure 2 (Batcheldor 2008). These plots show the M- σ relation (represented by a solid line) together with a set of dashed lines corresponding to the maximum distance at which the mass can be measured for a black hole of a given mass. The left-hand panel shows this for HST, while the right-hand panel shows the corresponding distances for a diffraction-limited telescope with ~0.01” resolution. (Left): for HST, even a ~10^9 $M_\odot$ black hole can only be measured by HST up to ~160 Mpc. (Right) for a ~0.01” PSF, the mass of such sources can be measured up to ~1 Gpc (z~0.5), and hence at much larger distances, since the angular size scale changes relatively slowly above this redshift.

Based on the typical size scales of gas disks around nearby SMBHs in the local universe, a spatial resolution of at least 100 pc is required to be able to resolve the disk sufficiently well to obtain a measurement of the mass: for a disk of radius 200 pc, at least two resolution elements (100 pc) are required (eg. Harms et al. 1994, ApJ 435, L35). With a standard lambda-CDM cosmology, the following limits are then obtained for telescopes of different apertures, assuming they are diffraction-limited above 6000A (as is the case with HST). The approximate number of potential targets is calculated using current models of black hole growth, for each redshift volume. The redshift limit of 7 for the 16 m telescope just reflects the fact that it can resolve 100 pc at all lower redshifts as well; beyond z~7 all the emission would shift into the IR but can potentially still be resolved by a 16m. At z=1.6 (where 100 pc would subtend the smallest angular scale, namely 0.012"), a 16m can still achieve the required resolution. An 8m, diffraction-limited at 3000A (thus 0.01") could potentially also observe targets up to z~1.6, but would lose them at higher redshifts since Lyman-alpha would be redshifted to wavelengths longer than 3000A, and the PSF FWHM of the 8m would increase to broader values.

To resolve such disks out to cosmological distances (z ~ 5 or more) would require a resolution ~10 mas, achievable with an 8m telescope diffraction-limited to 3000Å or a 16m telescope diffraction-limited to 6000Å, which would provide resolved images and spectra of structures associated with accretion disks in a rich variety of UV emission lines up to the reionization epoch. It should be pointed out that future ground-based telescopes will likely also be diffraction-limited at least beyond 1 micron, thus potentially with a similar PSF (0.01" – 0.02" from J to K band). The future large ground-based telescopes would be complementary , rather than redundant with, space-based telescopes: ground-based telescopes are still limited to operating in very specific atmospheric windows in the IR and require the emission lines to be present in these windows, but can potentially probe to higher redshifts, while a space-based telescope would provide more uniform sample coverage, thereby their synergy would eliminate the "redshift desert" effect that has created problems in redshift evolution studies to date.

Telescope size	Best resolution (diff. limited at 6000A)	Highest redshift at which 100 pc can be resolved with UV/opt	Number of potential SMBH targets
2m	**0.08"**	**0.06**	**10**
4m	**0.04"**	**0.10**	**30–100**
8m	**0.02"**	**0.36**	**1,000–3,000**
16m	**0.01"**	**7.00**	**20,000–60,000**

2.2 Reverberation Mapping

In addition to resolving the outer accretion disks, the inner structure of the matter falling into the SMBH could be probed, down to just a few Schwarzschild radii, by means of reverberation mapping. The standard model for the accretion disk around the SMBH in AGN postulates that the gas within the central few rg becomes extremely hot, optically thin and geometrically thick (e.g., Rees 1982, Narayan & Yi 1994). The gravitational radius for a typical SMBH with mass ~ 10^9 $M_\odot$ is $r_g \sim 10^{15}$ cm; it is this central region that is therefore generally identified as being the source of the X-ray and line emission observed in AGN. Although the material emits in the X-rays, in order to carry out reverberation mapping it is necessary to study a wide variety of UV/optical emission lines of differing ionization levels, in order to map the response of the broad-line region (BLR) to changes in ionizing flux and hence provide a direct measure of the black hole mass. This region is several orders of magnitude beyond the spatial resolution limit of any current telescope, but by means of reverberation mapping has been very successfully probed for a handful of objects in the local universe. A telescope with a spectral resolution of R ~ 30,000 , a hundred times the sensitivity of HST and high-contrast imaging in the UV/optical regime would provide a quantum leap in telescope capability that would enable this technique to be extended to the cosmological distances needed to truly probe the cosmic evolution of black holes.

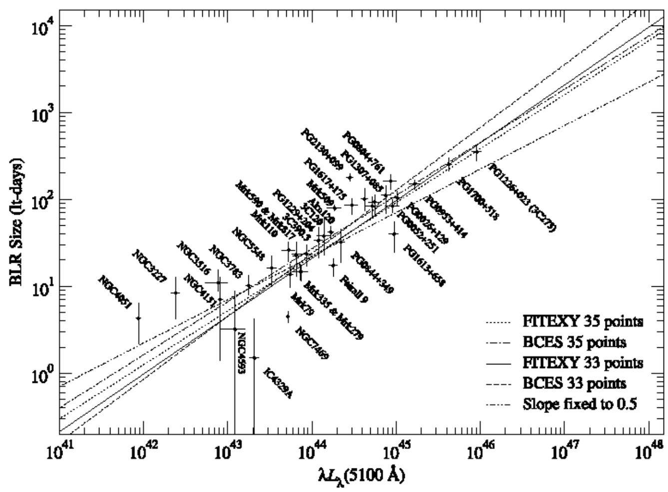

Fig. 3. Relationship between AGN luminosity and BLR size determined from reverberation mapping (Kaspi et al. 2007). These sources are all in the very nearby local universe; a large diffraction-limited space-based telescope (for UV/optical) or ground-based (for NIR) will enable such studies to be extended to cosmological distances, for the first time enabling a full understanding of how the detailed physical properties of black holes evolve with cosmic time up to the earliest epochs.

The high spectral resolution is required in order to provide reliable information on the line profiles, which change as a result of changes in ionization parameter across the BLR, while the increase in aperture is required simply because high S/N is needed for these studies, and successful BLR mass determination studies to date have been carried out only in the local universe. This technique is complementary to dynamical studies since in these sources, the ~100pc-scale gas is too diluted by the flux fron the unobscured AGN to enable dynamical studies to be carried out, therefore BLR reverberation mapping provides the only way to measure the mass for these sources. Many of the relevant high-ionization lines are in the UV, therefore a large UV/optical space-based telescope could carry this study forward from z~0.1 to z~2, while large diffraction-limited ground-based telescopes could extend thus further to z~5-6 or beyond, using UV lines redshifted into the IR.

3. Summary

As our next steps in exploring the nature between galaxies and their central SMBHs, we are left with several key questions surrounding the nature of SMBHs: How do SMBHs and galaxies grow together over cosmic time? Do the scaling relations evolve at high redshift (z>1)? What is the upper limit to the black hole mass function? In addition, there are only 3 cases where the available spatial resolution has been able to rule out all of the contending theories to the presence of SMBHs. The most effective way to generate a significant number of SMBH masses is to use gas and stellar dynamics derived from optical wavelengths. Currently planned ground-based facilities will not be able to complete a comprehensive study of SMBHs; their instrument suites lack the requirements for accurate SMBH mass determinations and they may be limited by the effects of the Earth's atmosphere. For a significant step forward in providing large samples of SMBH masses, a large aperture space-based telescope is required, while future large ground-based telescopes could provide good complementary follow-up of smaller samples. A 16-meter, optically optimized UV/optical space telescope would provide an unrivaled laboratory for SMBH physics. Such a telescope will be able, with little complication, to sample SMBH masses up to z~5 at least, limited primarily not so much by resolution but by surface brightness dimming at higher redshift. This would create such a large number of high quality SMBH mass estimates, in such a variety of host systems, that we would finally understand the nature of SMBH demographics through a significant portion of cosmic history.

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