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SUPERMASSIVE BLACK HOLES

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1. INTRODUCTION

Supermassive black holes (SMBHs) represent an important aspect of galaxy evolution theory that remains at the frontier of modern research. Like their stellar-mass versions, SMBHs have Schwarzschild radii, prevent light from escaping their event horizons and form accretion disks (ADs). Understanding SMBH origin and growth is of central importance in extragalactic astronomy due to their connection with the evolution of galaxies (Kelly et al. 2010). This stems from a number of observed relations with the properties of host galaxies, such as the mass of the baryonic component, the luminosity of a bulge, the velocity dispersion of stars (the $M_\bullet$–σ relation[2]) to name a few. There is a fundamental link between SMBHs and their hosts (Beifiori et al. 2012; Novak et al. 2006). SMBHs exist at the centers of the majority of normal galaxies and are "central engines" powering active galactic nuclei (AGN), and in the nuclei of quiescent galaxies are thought to be remnants of past AGN activity. The demography of local galaxies suggest that every galaxy hosts a quiescent black hole (Natarajan & Treister 2009) yet the origin of these objects is still poorly understood.

2. SUPERMASSIVE BLACK HOLES IN ACTIVE GALAXIES AND QUASARS

Since the discovery of quasars in 1963 many hypotheses have been proposed to explain their luminosities, including supernova explosions, supermassive stars, giant pulsars and SMBHs, the latter being the most plausible due to coherent arguments presented by Lynden-Bell (1969). This holds on several pillars. First, nuclear reactions are inefficient ($\epsilon_{nuclear} \sim 0.7\%$) in producing energy, resulting in high amounts of waste mass[3], if compared to SMBH ($\epsilon_\bullet \sim 9\%$) that converts and releases gravitational energy as thermal radiation by accreting infalling material (Merloni et al. 2004). Second, AGNs flicker – they vary in brightness rapidly over time intervals as short as 3 hours (and some flare even on time scales of minutes – e.g. MCG 6-30-15), and this puts an upper limit on their size because they cannot vary in brightness faster than light can travel across them. Third, quasars that exhibit the most flickering are assumed to form relativistic jets beamed towards the observer. This would not be possible without relativistic motions, that is at speeds comparable with the speed of light. Indeed, radio jet plasma knots are detected at superluminal speeds which can be explained by deep gravitational wells of SMBHs, i.e. strong gravitational potential fields surrounding them. Finally, collimated AGN jets "remember" the direction they eject on for as long as 10^7 yr. The natural explanation for this phenomenon is a single rotating body acting as a gyroscope (Ho & Kormendy 2000). Thus, the basic model of quasar emission includes accreting SMBH with the inner portions of the AD, due to the Kepler's third law, rotating faster and producing friction against the outer portions. This heats the accretion material up to 10^5 K and the gas in AD glows, emitting radiation at a broad range of wavelengths, from radio to γ-ray. All the major types of objects in, as Barger (2004) puts it, AGN menagerie—quasars, radio galaxies, Seyfert nuclei, blazars, low-ionization nuclear emission regions (LINERS), BL Lacertae objects to name a few—can be explained by accreting SMBH, and this comprises what is called the "AGN paradigm" (Ferrarese & Ford 2005).

Table 1
SMBH Search Methods

Method	$M_\bullet$ ($M_\odot$)	ρ_{typ} ($M_\odot$ pc^{-3})
Fe Kα line	N/A	N/A
Reverberation Mapping	10^6–4×10^8	$\gtrsim 10^{10}$
Stellar Proper Motion	3×10^6	4×10^{16}
H_2O Masers	2×10^6–4×10^7	$> 10^9$
Gas Dynamics (optical)	7×10^7–4×10^9	$\sim 10^5$
Stellar Dynamics	10^7–3×10^9	$\sim 10^5$

Note. — $M_\bullet$ denotes the range in the detected SMBH masses; ρ_{typ} is corresponding implied central mass density.

3. DETECTION METHODS AND OBSERVATIONAL EVIDENCE

The commissioning of advanced high-resolution instruments, such as the *HST* and *VLBA*, as well as improvements in speckle imaging techniques provided us with a wealth of evidence of SMBH existence. Because the research in this field is so rapid, this attempt to summarize the success of one or another method of SMBH detection should be treated as a historical snapshot – see table 1 based on data from Barger (2004). The most generally used methods are dynamical studies of gas and stars at large distances from SMBH but still within its gravitational field. The stellar dynamics method is based on the measurement of kinematics of central galactic regions (velocity distribution of stars) close to the SMBH sphere of influence. The results are combined with high-resolution imaging to construct a dynamical model of a galaxy. A SMBH is introduced into the model in order to obtain the best fit to the observed stellar dynamics. The model with the minimal χ^2 provides the best $M_\bullet$ and M/L correlation (Bender & Saglia 2007). For external galaxies, the method based on kinematic measurements using spatially-resolved water masers in the dusty torus surrounding a black hole provided one of the best detections of SMBHs in NGC 4258 (Miyoshi et al. 1995). The indirect detection method is based on the broad iron

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[2] In this text, subscript $\bullet$ denotes a black hole.
[3] ϵ is radiative energy-generating efficiency.

Kα emission at 6.44 KeV that is thought to arise from a rapidly rotating AD within a few Schwarzschild radii of the central SMBH (Pounds et al. 1990). Finally, a technique called reverberation mapping is based on a specific time delay between the emission-line and the continuum variations of AGN arising due to the light travel time as excitation propagates throughout the AGN's broad-line region (BLR; high-density gas at $\sim 10^4$K moving supersonically). Given there is a relationship between the two fluxes, this allow to estimate the size of the BLR and, subsequently, the mass of the central object.

4. MASSES, FORMATION AND IMPLICATIONS

Theoretical upper limit of SMBH masses in our universe is estimated to be $\sim 3 \times 10^{10} M_\odot$ (Kelly & Merloni 2012). While we do not detect AGNs with masses $\lesssim 10^5 M_\odot$ in typical active galaxies it appears to be because black holes of lower mass are simply not supposed to produce broad emission lines with strength required by our detectors, in other words our observational methodology may be biased against SMBHs with lower masses (Chakravorty et al. 2014; Sanders 2012). As an example of a known host of a lower-mass black hole the dwarf Seyfert 1 galaxy POX 52 can be suggested thought—because of its AGN spectrum, accretion luminosity and other properties—to contain a black hole of $1.6 \times 10^5 M_\odot$. It is worth mentioning the discovery paper (Barth et al. 2004) refers to it as an intermediary mass black hole (IMBH), and other sources (Volonteri 2010) refer to black holes with masses of the order of $10^5 M_\odot$ simply as massive black holes (MBHs), bridging the gap between supermassive and stellar-mass black holes.

The discovery of luminous high-redshift $z \sim 6$ quasars by Sloan Digital Sky Survey implies very early formation of SMBHs, when the universe was less than 1 billion years old (Li et al. 2007). The luminosities of these quasars indicate SMBHs with masses of $\sim 10^9 M_\odot$ were formed at these early times already. This observation places certain time constraints on applicable formation models of these black holes. Unlike stellar-mass versions, the formation of SMBHs does not require extreme material densities, such as those observed in supernovae explosions. There are three basic scenarios of SMBH formation, depending on whether the black hole is a cause or an effect of galaxy formation: (i) collapse of a primordial metal-free gas or a massive Population III star to SMBH in early universe, and the galaxy forms around it; (ii) galaxy forms and enters into Population II phase, and SMBH forms by accreting gas clouds and stars; and (iii) hybrid scenario whereby there is a single master process generating both the galactic bulge and the SMBH at the same time. A good overview is available from outstanding work by Meier (2009).

In the last few years, within the first scenario we are finding models involving collapse of gas in pre-galactic haloes taking preference over models of the collapse of primordial stars. This looks like to be the most promising route to the rapid formation of massive black holes of 10^4–$10^6 M_\odot$ masses (Regan & Haehnelt 2009; Mayer et al. 2010) that act as seeds for the SMBH growth. During this process, a pre-galactic dark matter haloes with $T_{vir} \gtrsim 10^4$K coalesce[4], forming either supermassive stars or quasi-stars, stellar-mass black hole seeds or star clusters, either of them collapsing further into massive black holes. Despite Population III stars are capable to form smaller stellar-mass black holes, sustained accretion of such low mass seeds at or above Eddington rate is required to arrive at billion solar mass SMBHs powering $z \sim 6$ quasars, thus that scenario seems less plausible. There are direct SMBH formation scenarios discussed with supermassive stars with $M_* = 10^4$–$10^8 M_\odot$, however more realistic in the early universe was the formation of stars of 50–200$M_\odot$ (Bromm et al. 2002). Such stars may collapse to black holes of comparative sizes, however this does not explain how much larger SMBHs were formed.

The second, accretion growth scenario may explain the $M_\bullet$–σ relation ($M_\bullet \propto \sigma^5$), however the problem is that most SMBHs do not accrete at all, probably because stars and particles have stable orbits with certain angular momentum and the matter density is too low to get rid of it by friction. As a practical example of this obstacle we can take the stability of our solar system. With abundant supply of gas and dust in galactic centers the question of how most of SMBHs remain quiescent and do not produce an AGN is still open (Fabian & Canizares 1988; Di Matteo et al. 1999).

SMBH masses are strongly correlated with their host galaxy bulge masses in the so called $M_\bullet$–M_{bulge} relation. This suggests a common mechanism linking the growth of both SMBH and galactic bulge. Based on the numerical simulations and galaxy formation models, galaxy mergers are proposed as the most likely candidates for this third, hybrid SMBH formation scenario. During such mergers of two galaxies of comparable sizes their central black holes merge and perturbations of the gas drive it inward, fueling the newly formed SMBH and giving start to quasar period in galaxy's history (Kauffmann & Haehnelt 2000). This model fits well with observed evolution of galaxies and reproduces quantitatively the relation between black hole mass and bulge luminosity (the $M_\bullet$–L relation). Hybrid models also explain the $M_\bullet$–σ relation well.

5. $M_\bullet$–M_{BULGE} RELATION

Early suggestions that the masses of massive dark objects at the centers of nearby galaxies exhibit correlation with the mass of the hot stellar component of their hosts appear in the works of Kormendy (1993); Kormendy & Richstone (1995), found by Magorrian et al. (1998) to be $M_\bullet \sim 0.005 M_{bulge}$ via dynamical modeling. This has later been refined with greater accuracy to $M_\bullet \sim M_{bulge}^{1.12\pm0.06}$ by Häring & Rix (2004) using data from *Hubble Space Telescope* – see figure 1. The mass relation is found to be as tight as the $M_\bullet$–σ relation and it provides good evidence that black holes play a key role in the evolution of galaxies. Despite that velocity dispersions are easy to measure in local universe, the $M_\bullet$–M_{bulge} relation is important because the bulge mass can be estimated for non-local objects ($z \gtrsim 2$) via the measured luminosity and an upper limit of the stellar

[4] Characteristic temperature T_{vir}, referred to as the *virial temperature* of the halo, is the temperature the gas reaches during *virialization*. The system exists in a gravitationally stable and relaxed state, or equilibrium, when it is virialized, according to the virial theorem which states that $2K + W = 0$, where K is the total kinetic energy and W is the total potential energy of the system. For more information consider Carroll & Ostlie (2006).

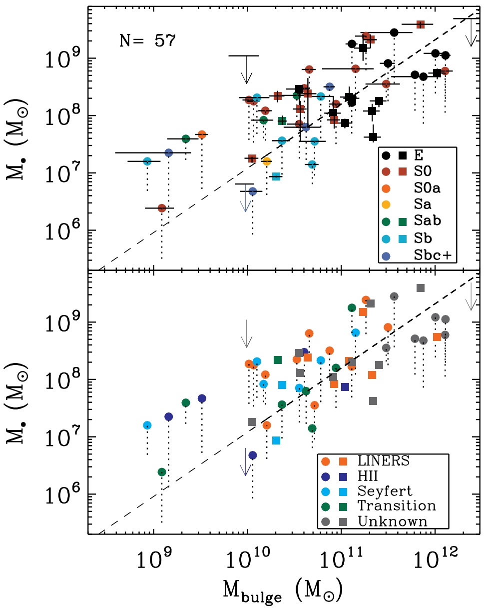

Figure 1. The slope of Häring & Rix (2004) $M_\bullet$–M_{bulge} relation (dashed line) for a total of 57 galaxies, plotted according to morphological type (upper panel) and nuclear activity (lower panel). The error bars for M_{bulge} are shown only in the upper panel for clarity. Image from the paper by Beifiori et al. (2012).

mass-to-light ratio, derived from the maximal age of the stellar population at that redshift.

6. CONCLUSIONS

Barger (2004) noted a peculiar contrast of our progress in understanding supermassive and stellar-mass black holes. It took 60 years of theoretical groundwork to produce the first detection of Cygnus X-1, however despite for the existence of SMBHs we now have overwhelming observational evidence, the theoretical background is still lacking. There are many fundamental questions and concerns pertaining SMBH and host galaxy relations. For example, were relations constant throughout the history of the universe? Do they scale linearly? What is the nature of the exceptions, SMBH-outliers like M33 and NGC 205 (Valluri et al. 2005)? How frequent are they, do they reside in all types of galaxies? How many supermassive binary BHs and how they evolve and coalesce? What is the fraction of the off-center SMBHs? Those questions can be answered by high resolution observations and we are already at the limits of resolution of ground based systems due to atmospheric turbulence, even with adaptive optics technology. Future missions, such as *IXO* and *JWST* will have technical capabilities to detect accreting black holes at $z \gtrsim 6$, yet it is estimated that a larger (16 m) space-based UVOIR (ultraviolet, optical, near-infrared) telescope will advance our knowledge of SMBHs significantly as it will enable to observe out to $z = 10$, or across 96% of all cosmic history with sufficient resolution and sensitivity (Batcheldor & Koekemoer 2009).

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