CLASSICAL BULGES, SUPERMASSIVE BLACK HOLES, AND AGN FEEDBACK: EXTENSION TO LOW-MASS GALAXIES

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ABSTRACT

The empirical model of Lu et al. for the relation between star formation rate and halo mass growth is adopted to predict the classical bulge mass ($M_{cb}$)–total stellar mass ($M_*$) relation for central galaxies. The assumption that the supermassive black hole (SMBH) mass ($M_{\text{BH}}$) is directly proportional to the classical bulge mass, with the proportionality given by that for massive galaxies, predicts a $M_{\text{BH}}$–$M_*$ relation that matches well the observed relation for different types of galaxies. In particular, the model reproduces the strong transition at $M_* = 10^{10.5} - 10^{11} M_\odot$, below which $M_{\text{BH}}$ drops rapidly with decreasing $M_*$. Our model predicts a new sequence at $M_* < 10^{10.5} M_\odot$, where $M_{\text{BH}} \propto M_*$ but the amplitude is a factor of ~50 lower than the amplitude of the sequence at $M_* > 10^{11} M_\odot$. If all SMBHs grow through similar quasar modes with a feedback efficiency of a few percent, then the energy produced in low-mass galaxies at redshift $z > 2$ can heat the circumgalactic medium up to a specific entropy level that is required to prevent excessive star formation in low-mass dark matter halos.

Key words: galaxies: evolution -- galaxies: formation

1. INTRODUCTION

The co-existence of supermassive black holes (hereafter SMBHs) and early-type galaxies, such as elliptical galaxies and the bulges of spiral galaxies, have been found to be ubiquitous (e.g., Kormendy & Richstone 1995). A tight correlation has been observed between SMBH mass and the stellar mass and velocity dispersion of the host spheroid component. SMBH mass is roughly proportional to the spheroid mass with a ratio between the two of about 0.1% (McLure & Dunlop 2002; Haring & Rix 2004) to 0.5% (see Kormendy & Ho 2013 for a review).

The observed scaling relation suggests that the growth of both SMBHs and the spheroid components are driven by similar physical processes. The most popular scenario is mergers of galaxies, in which a large amount of cold gas originally supported by a rotation disk can lose angular momentum and sink toward the center to fuel both SMBH growth and star formation. In addition, the energy feedback from the active galactic nucleus (AGN) associated with SMBH accretion may heat and/or eject the cold gas, suppressing both star formation and SMBH growth (e.g., Springel et al. 2005). Indeed, with plausible assumptions about AGN feedback and about how star formation and SMBH growth are related to the cold gas density, numerical simulations and semi-analytical models can reproduce the general trend in the observed scaling relation (e.g., Croton 2006; di Matteo et al. 2008). In addition to the merger scenario, other mechanisms have also been proposed, such as the direct accretion of low angular momentum cold flow (di Matteo et al. 2012; Dubois 2012), the intense gravitational instability in clumpy disks (Bournaud 2011), and some secular processes (Dubois 2014). However, it is not clear how much these mechanisms contribute to the connection between SMBHs and their host galaxies.

Recent observations have extended the detections of SMBHs and their mass measurements to late-type galaxies and to galaxies in the low-mass end (e.g., Filippenko & Ho 2003; Greene & Ho 2004, 2007; Greene et al. 2008; Jiang et al. 2011a, 2011b). These observations indicate a number of interesting deviations from the scaling relation derived from massive, early-type galaxies. First, it was found that many late-type spiral galaxies, which do not have a significant classical bulge component but contain a pseudo-bulge formed through secular evolution of the disk, do contain central SMBHs. At a fixed bulge mass (luminosity), the SMBH masses are about a factor of 5–10 lower than expected from the correlation seen for classical bulges, and the scatter is also significantly larger (see Kormendy & Ho 2013). Equivalently, the correlation between the central BH and the bulge is dramatically bent (Graham 2012; Graham & Nicholas 2013; Scott et al. 2013). Second, SMBHs have also been observed in dwarf galaxies, such as dwarf spheroids and dwarf ellipticals (e.g., Barth et al. 2004; Reines et al. 2013). It is still unclear whether late-type SMBHs and low-mass galaxies have formed through the same processes as in classical bulges, or through completely different mechanisms.

Recent modeling of Lu et al. (2014a, 2014b) of the observed populations of galaxies at different redshifts shows that all galaxies contain a classical bulge component produced by major galaxy–galaxy mergers. The significance of such a classical bulge depends strongly on the total stellar mass of the galaxy. In galaxies with sub-Galactic masses, this component is old in stellar population and smaller in stellar mass by an order of magnitude than pseudo-bulges (e.g., Fukugita et al. 1998), and therefore may be missed in observations due to the presence of other dominating components. In this paper, we demonstrate that the SMBHs hosted by late-type galaxies can also be explained by co-evolution with the classical bulge components potentially hidden in these galaxies. In Section 2, we predict the relation between the classical bulge mass and total stellar mass of galaxies, and in Section 3 we examine its implications for the SMBH mass–galaxy mass relation. We will see that applying the observed $M_{\text{BH}}$–$M_{cb}$ relation to the modeled galaxies reproduces well the observed relation...
between $M_{\text{BH}}$ and the total stellar mass of the host galaxies. This suggests that the co-evolution of SMBHs is predominantly with classical bulges formed through mergers, while secular evolution does not play a major role in the growth of SMBHs. We study the implications of our results for AGN feedback in Section 4, and summarize in Section 5.

2. CLASSICAL BULGES

In this section, we provide a very brief description of the model of Lu et al. (2014a, 2014b), adopted here to make predictions for the masses of classical bulges in galaxies, referring the reader to the original papers for details.

The star formation rate (SFR) of a central galaxy in a halo at a given redshift $z$ is assumed to depend only on the virial mass of the host halo, $M_h(z)$ and $z$. Simple broken power laws are adopted for the mass and redshift dependence. The build-up of individual dark matter halos is modeled using the halo merger tree generator developed by Parkinson et al. (2008). This is a Monte Carlo model based on a modified treatment of the extended Press–Schechter formalism and calibrated with $N$-body simulations (see Cole et al. 2008). The stellar masses and luminosities of the galaxies in a halo and in its progenitors are obtained by going through its merger tree and integrating the SFR with an assumed stellar evolution model and a stellar IMF. The exact form of the mass and redshift dependence is inferred from a set of observational constraints using a Bayesian technique.

In Lu et al. (2014a, 2014b), two model families are considered in detail. The first one, labeled Model II in these papers, is constrained by the observed stellar mass functions (SMFs) in the redshift range $0–4$. Model II represents a class of “Slow Evolution” models studied in the literature (Yang et al. 2012, 2013; Behroozi et al. 2013a, 2013b): virtually all stars form in dark matter halos in a narrow range of halo mass $10^{11} h^{-1} M_\odot \lesssim M_h \lesssim 10^{12} h^{-1} M_\odot$ over a large range of redshift. For this model, galaxy–galaxy mergers are a significant channel of mass assembly only for the most massive galaxies in halos with $M_h > 10^{13} M_\odot$; galaxies with lower masses acquire their stellar mass mainly through in situ star formation.

The second one, the fiducial model labeled Model III, is constrained not only by the SMF but also by the luminosity function of cluster galaxies (Popesso et al. 2006). The latter shows a steep upturn at the faint end, which provides an important constraint on star formation histories in low-mass halos. For halos more massive than $10^{11} M_\odot$, Models III and II are consistent with each other. In halos with $M_h < 10^{11} M_\odot$, however, Model III predicts more efficient star formation at $z > 2$. This efficient star formation phase during the early epoch leads to some interesting predictions that are supported by recent observations, such as the presence of a significant old stellar population in dwarf galaxies (Weisz et al. 2011) and the steep slopes of the galaxy stellar mass and SFR functions (Smit et al. 2012). The efficient star formation during the early epoch is accompanied by frequent galaxy–galaxy mergers, as shown in Lu et al. (2014b, see the lower left panel of Figure 4 in their paper), which is expected to leave other important imprints in the galaxy population.

In this paper, both models are used to study the formation of classical bulges and the connection between SMBHs and their host galaxies. Model II is also included to show how star formation at high $z$ in low-mass halos can affect our model predictions.

Following Lu et al. (2014b), we assume that the stellar disks of galaxies form only through in situ star formation, and that a major merger can transform a disk into a classical bulge. Thus the mass of the stellar disk, $M_{\text{d,sh}}$, is simply the total mass of stars formed in situ after the last major merger, while the mass of the classical bulge, $M_{\text{cb,sh}}$, is just the difference between the total stellar mass, $M_*$, and $M_{\text{d,sh}}$. Figure 1 shows the relation between $M_{\text{d,sh}}$ and $M_*$ for central galaxies predicted by Model II (left) and Model III (right). Due to frequent major mergers, the most massive galaxies are completely dominated by the classical bulge.
bulge components. Both models predict a strong transition at $M_* \sim 10^{11} M_\odot$. For galaxies in the mass range $2 \times 10^{10} M_\odot - 10^{11} M_\odot$, in situ star formation begins to quench at the present time while major mergers are sparse but not negligible. Consequently, these galaxies experienced either one or no major merger in the recent past, so they are either dominated by a classical bulge or remain disk dominated, producing the strong bimodality in the $M_\text{cb} - M_*$ plane. Model II predicts that the mass in the classical bulge component is much smaller than the total stellar mass of the galaxy. Model III, however, predicts a rapid decline of SMBH mass with decreasing stellar mass, $M_{\text{BH}} \propto M_*^{-2.5}$, with large scatter. In contrast, Model III predicts a new $M_{\text{BH}} \propto M_*$ sequence, but with the amplitude dropped by a factor of $\sim 50$ relative to that at the massive end. At the moment, the small number of observational data points appear to be better matched by Model III, but no reliable conclusion can yet be reached without more data and a better understanding of observational selection effects. It is clear, however, that Model III, which is favored by a large set of observational data, does predict that many galaxies with sub-Galactic masses host SMBHs with $M_{\text{BH}} = 10^5 - 10^6 M_\odot$.

3. IMPLICATIONS FOR SUPERMASSIVE BLACK HOLES

Given that all galaxies are expected to contain classical bulges formed through mergers of galaxies, we test the hypothesis that SMBHs are only due to classical bulges. The correlation between SMBHs and classical bulges from Kormendy & Ho (2013) is

$$\frac{M_{\text{BH}}}{10^9 M_\odot} = \left( 0.49^{+0.06}_{-0.08} \right) \left( \frac{M_{\text{cb}}}{10^{11} M_\odot} \right)^{1.16 \pm 0.08} \quad (1)$$

The intrinsic scatter in $M_{\text{BH}}$ is about 0.29 dex at fixed $M_{\text{cb}}$. We apply this relation to the classical bulges obtained in the last section to predict an SMBH mass for each model galaxy. The red curve in Figure 2 shows the mean of the predicted SMBH mass as a function of the total stellar mass, and the isodensity contours show the distribution of galaxies in the $M_* - M_{\text{BH}}$ plane. Results are presented for both Model II (left) and Model III (right). The predicted relations are compared with the observational data compiled by Kormendy & Ho (2013), shown as colored points with different styles representing different systems, as well as the catalog from Graham & Scott (2013). The two outliers, N4468B and N1277, probably have significantly reduced stellar masses due to strong stripping. The black open circles are data from Graham & Scott (2013). The light blue point at the bottom left corner is the dwarf Seyfert 1 galaxy Pox 52 (Thornton et al. 2008).

Figure 2. Relation between the SMBH mass and the total galaxy stellar mass predicted by Model II (left) and Model III (right). The red line is the median of the model prediction in each stellar mass bin and the yellow band encompasses 90% of the galaxies in the corresponding bins. For comparison, isodensity contours in the $M_{\text{BH}} - M_*$ plane are also shown. The colored data points were compiled by Kormendy & Ho (2013). The two outliers, N4468B and N1277, probably have significantly reduced stellar masses due to strong stripping. The black open circles are data from Graham & Scott (2013). The light blue point at the bottom left corner is the dwarf Seyfert 1 galaxy Pox 52 (Thornton et al. 2008).
efficient and gas-rich mergers of galaxies are still frequent (Lu et al. 2014b). The consequence of such SMBH formation for the evolution of their host galaxies is discussed in the next section.

For comparison, we also plot the SMBH mass function estimated by Shankar et al. (2009), which is widely adopted in the literature. Without distinguishing between pseudo-bulges and classic bulges, their estimates assumed that all late-type galaxies have a bulge-to-total light ratio of \( \approx 0.27 \) (Fukugita et al. 1998). This ratio is about seven times larger than our prediction for classical bulges, and is also the reason why their mass function is much higher than ours at \( M_{\text{BH}} \sim 10^{7.5} M_\odot \).

4. AGN FEEDBACK FROM LOW-MASS GALAXIES

As an SMBH grows, the power of the energy output can be written as

\[
\frac{dE}{dt} = \epsilon M_{\text{BH}} c^2,
\]

where \( \epsilon \) is an efficiency factor. The total energy output is

\[
E = \tau M_{\text{BH}} c^2,
\]

where \( \tau \) is the mean efficiency. Since in our model \( M_{\text{BH}} \) is roughly proportionally to \( M_\text{bul} \) and the energy feedback from star formation is also \( \propto M_\text{bul} \), the above equation (and our modeling below) still applies even if the feedback effect of classical bulge stars is taken into account.

Suppose a fraction \( f_B \) of this energy output is eventually transferred to and retained in a total amount of gas of mass \( M_{\text{gas}} \) and we write this mass in terms of the mass of the host halo: \( M_{\text{gas}} = \lambda f_B M_\text{bul} \), with \( \lambda \) being a constant loading factor and \( f_B \approx 0.17 \) the universal baryon fraction. The effective temperature of the gas due to the energy transfer can then be written as

\[
\frac{kT_{\text{eff}} M_\text{bul}}{\mu} = f_B \tau M_{\text{BH}} c^2,
\]

where \( \mu \) is the mean molecular weight of the gas. This can be written in a more useful form:

\[
\frac{kT}{\mu} = f_B \frac{\tau c^2}{\lambda f_B} \left( \frac{M_\text{bul}}{M_\text{host}} \right) \left( \frac{M_\text{gas}}{M_\text{bul}} \right).
\]

As shown in Lu et al. (2014b), for dwarf galaxies with stellar masses between \( 10^8 \) and \( 10^9 M_\odot \) at \( z \sim 3 \), which were the progenitors of present day sub-Galactic galaxies \( (10^2-10^3 M_\odot) \), \( M_{\text{BH}}/M_\text{bul} \approx 10^{-2.5} \) (see the bottom right panel in Figure 3 of their paper). These progenitors are typically bulge dominated because of galaxy–galaxy major mergers. If we adopt a bulge to total ratio of \( 1/2 \) and scale Equation (1) up by a factor of 3 for these high-redshift progenitors (Kormendy & Ho 2013), then we get \( M_{\text{BH}}/M_\text{bul} \approx 0.3\% \). Assuming \( \tau \) to be 0.6 times the proton mass, and \( \tau = 0.1 \) as is usually assumed for an AGN in the quasar mode, we have

\[
T_6 \approx 1.0 \times \left( \frac{f_B}{0.03} \right) \left( \frac{\Lambda_{-23}}{10} \right)^{-1},
\]

where \( T_6 \equiv T/10^6 \) K.

For the current cosmology, the age of the universe at \( z > 1 \) is roughly

\[
t \approx 3.0 \times \left( \frac{1 + z}{3} \right)^{-3/2} \text{Gyr},
\]

and the cooling time of the gas medium with an over-density \( \delta \) and temperature \( T \) at \( z \) is

\[
t_{\text{cool}} \approx 3.0 \times \left( \frac{1 + z}{3} \right)^{-3} \Lambda_{-23}^{-1} T_6 \left( \frac{1 + \delta}{60} \right)^{-1} \text{Gyr},
\]

where \( \Lambda_{-23} \) is the cooling function in units of \( 10^{-23} \text{erg s}^{-1} \text{cm}^2 \). Setting \( t_{\text{cool}} = t \) and using the fact that \( \Lambda_{-23} \approx T_6^{-1} \) for a low-metallicity gas with temperature in the range \( 10^5-10^6 \) K, we get

\[
T_6 \approx 1.0 \times \left( \frac{1 + z}{3} \right)^{3/4} \left( \frac{1 + \delta}{60} \right)^{1/2}.
\]

This temperature corresponds to a specific entropy

\[
S \equiv \frac{kT}{n_e c^2} \approx 15.0 \times T_6 \left( \frac{1 + \delta}{60} \right)^{-2/3} \left( \frac{1 + z}{3} \right)^{-1/3} \text{keV cm}^2
\]

\[
\approx 15.0 \times \left( \frac{1 + \delta}{60} \right)^{-1/6} \left( \frac{1 + z}{3} \right)^{-5/6} \text{keV cm}^2.
\]

Note that \( S \) depends only weakly on \( \delta \) at a given \( z \).

If the medium is heated above the temperature given by Equation (9), then gas cooling will be suppressed. Thus, for the AGN feedback to have a significant impact on subsequent galaxy formation and evolution, the temperature given by Equation (6) should be higher than that given by Equation (9). This gives a constraint on \( \lambda \)

\[
\lambda \bar{z} \lesssim \frac{f_B}{0.03} \left( \frac{1 + z}{3} \right)^{-3/4} \left( \frac{1 + \delta}{60} \right)^{1/2}.
\]

Numerical simulations show that to reproduce the observed \( M_{\text{BH}} \)-galaxy velocity dispersion relation requires 5% of the
total energy output be coupled with the surrounding gas (e.g., di Matteo et al. 2008). The energy will propagate through the host galaxies and the host halos as blast waves or super-bubbles in which radiative cooling is expected to be slow because of the low-density of the halo gas. So \( f_\nu \) is not expected to be much lower than a few percent. The over-density \( \delta \approx 60 \) is about the value appropriate for the exteriors of dark matter halos. Finally, as shown in the previous section, most of the SMBHs in the dwarf galaxies formed at \( z > 2 \). Setting \( f_\nu \approx 0.03 \), \( \delta \approx 3 \) and \( \delta \approx 60 \) gives \( \lambda \lesssim 8 \). As shown in Zhao et al. (2009), a low-mass halo has typically increased its mass by a factor of 5 since \( z \sim 3 \). Thus, the AGN feedback is, in principle, capable of affecting all the gas to be accreted by a halo in its subsequent growth.

How might such a feedback proceed? In general, the impact of the feedback from an AGN is expected to first affect the gas close to the galaxy. Since the intergalactic medium (IGM) is expected to be clumpy and filamentary, the dense part of the medium may still be able to cool and circumvent total disruption by the wind. This part of the gas can then move against the outflow toward the halo center to feed the galaxy and SMBH. The growth of an SMBH and star formation may thus go through a number of bursts, as the dense clouds are accreted episodically. As the local medium is heated and expands, an negative gradient of entropy may develop, producing gas convection and mixing gas of different specific entropies. Eventually a large envelope of roughly constant specific entropy may develop around each low-mass halo. This process continues until most of the gas in the IGM around the galaxy has a specific entropy such that its radiative cooling time is comparable to the age of the universe. As demonstrated above, the likely epoch for this to be accomplished is at \( z \approx 5 \) to 3, and the specific entropy is of the order of 10–15 keV cm\(^2\).

The subsequent formation and growth of dark matter halos are then in a preheated medium where gas accretion and cooling in low-mass halos can be reduced significantly. This scenario of galaxy formation in a preheated medium was first proposed in Mo & Mao (2002). As shown in Mo et al. (2005), Lu & Mo (2007), and Lu et al. (2014), the level of specific entropy predicted here is roughly what is needed to suppress gas accretion and star formation in low-mass halos to match the observed stellar mass and \( H_\text{I} \) mass functions at the low-mass end.

5. DISCUSSION

In this paper, we have shown that the observed SMBH masses are consistent with the assumption that they are directly proportional to the mass of the classical bulges of their hosts, even in late-type galaxies. In particular, this assumption combined with the classical bulge masses reproduces well the rapid decrease of \( M_{\text{BH}} \) with decreasing \( M_* \). Our Model III, constrained by various observations of galaxies, predicts a new low-mass sequence in the \( M_{\text{BH}}-M_* \) relation, where the SMBH mass is roughly proportional to galaxy mass, but with the amplitude \( \sim 50 \) times lower than that of the high-mass sequence.

The assumptions in and consequences of our proposed scenario can be tested with more detailed modeling. At the moment, it is still unclear whether SMBHs in low-mass and late-type galaxies form in a similar way as in their more massive counterparts. For example, it is unclear whether they grow from seeds similar to those for massive SMBHs, and whether their growth is also dominated by quasar modes, although they are predicted to be produced by mergers of gas-rich galaxies. To answer these questions, observations of low-luminosity AGNs at high \( z \) and accurate determinations of the SMBH masses in low-mass galaxies are essential. If our scenario is correct, we expect to observe a large number of low-luminosity AGNs at \( z > 2 \) and a large number of SMBHs with masses in the range from \( 10^5 \) to \( 10^6 \) at \( z \sim 0 \). The classical bulges within which these SMBHs have formed are expected to be compact, not only because their host halos at \( z > 2 \) are small, but also because major galaxy–galaxy mergers can reduce the angular momentum of the cold disk gas, making the merger remnants even smaller. How such formation is related to the observed ultra compact dwarfs (UCDs, e.g., Norris et al. 2014 and references therein) is clearly an interesting and open question.

In our scenario, an implicit assumption is that secular evolution of galaxy disks does not play a major role in the growth of SMBHs. This assumption can be tested by observing barred disks, in which secular evolution is on-going, to see whether their AGN activities are elevated or not. So far observational evidence is negative for such elevation (e.g., Kormendy et al. 2011), but current data are still sparse.

We have also shown that the formation of SMBHs in low-mass galaxies provides a new scenario of preventative feedback, in which gas is prevented from being accreted into a dark matter halo due to preheating. Such a scenario is plausible based on our simple arguments, but the details need to be worked out. For example, how does the AGN-driven outflow propagates into the IGM and affect its properties? What is the structure of the circumgalactic medium produced in this way? Will such formation produce a multiphase medium (Mo & Miralda-Escude 1996) and how will it be observed in QSO absorption line studies? Can the interaction between the gas and dark matter reduce the phase space density of dark matter halos, as advocated in Mo & Mao (2004)? We will come back to some of these questions in the future.

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\footnote{For a singular isothermal halo defined so that the mean density within its virial radius is 200 times the mean density of the universe, the over-density at the virial radius is \( \delta \approx 66 \).}
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