COEVOLUTION BETWEEN SUPERMASSIVE BLACK HOLES AND BULGES IS NOT VIA INTERNAL FEEDBACK REGULATION BUT BY RATIONED GAS SUPPLY DUE TO ANGULAR MOMENTUM DISTRIBUTION

RENYUE CEN
Princeton University Observatory, Princeton, NJ 08544, USA; cen@astro.princeton.edu
Received 2015 January 30; accepted 2015 April 27; published 2015 May 18

ABSTRACT
We reason that without physical fine-tuning, neither the supermassive black holes (SMBHs) nor the stellar bulges can self-regulate or inter-regulate by driving away already fallen cold gas to produce the observed correlation between them. We suggest an alternative scenario where the observed mass ratios of the SMBHs to bulges reflect the angular momentum distribution of infalling gas such that the mass reaching the stable accretion disk is a small fraction of that reaching the bulge region, averaged over the cosmological timescales. We test this scenario using high-resolution, large-scale cosmological hydrodynamic simulations, without active galactic nucleus (AGN) feedback, assuming the angular momentum distribution of gas landing in the bulge region yields a Mestel disk that is supported by independent simulations resolving the Bondi radii of SMBHs. A mass ratio of 0.17 to 0.3% between the very low angular momentum gas that free falls to the subparsec region to accrete to the SMBH and the overall star formation rate is found. This ratio is found to increase with increasing redshift to within a factor of ~2, suggesting that the SMBH-to-bulge ratio is nearly redshift independent, with a modest increase with redshift, which is a testable prediction. Furthermore, the duty cycle of AGNs with high Eddington ratios is expected to increase significantly with redshift. Finally, while SMBHs and bulges are found to coevolve on ~30–150 Myr timescales or longer, there is indication that on still smaller timescales, the SMBH accretion and star formation may be less correlated.

Key words: cosmology: theory – galaxies: bulges – galaxies: formation – hydrodynamics – quasars: supermassive black holes – stars: formation

1. INTRODUCTION
There is mounting evidence that massive bulges in the nearby universe harbor central supermassive black holes (SMBHs) of mass $10^6–10^9 M_\odot$. The correlation between SMBH mass ($M_{\text{BH}}$) and the bulge (BG) mass ($M_{\text{BG}}$) or velocity dispersion ($\sigma$; e.g., Magorrian et al. 1998; Richstone et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002) suggests coevolution. Although alternative models for producing this observed correlation are available (e.g., Ostriker 2000; Adams et al. 2001; Colgate et al. 2003; Cen 2007), the correlation is often construed as evidence for active galactic nucleus (AGN) feedback to regulate the growth of SMBHs and bulges. The idea that AGN feedback may alleviate problems in galaxy formation models (e.g., Kauffmann & Haehnelt 2000; Croton et al. 2006; Somerville et al. 2008) further enhances its appeal. The three-dimensional hydrodynamic simulations successfully reproduced the observed $M_{\text{BH}}/M_{\text{BG}}$ ratio (e.g., Di Matteo et al. 2005; Hopkins et al. 2006), providing the physical basis for this scenario.

This Letter has two goals. First, we make a qualitative examination of the implications of the observed correlation between bulges and the central massive objects (CMOs), wherein the two follow a linear relation over four decades in mass. It is shown that neither the SMBHs nor the nuclear star clusters (NSCs) nor the stellar bulges could have played a dominant role in regulating the growth of any of the three components by blowing away a significant fraction of gas that already landed in the respective regions so as to produce the CMO–bulge relation. Second, an alternative model is put forth wherein the correlation between SMBH mass and bulge mass is dictated by the angular momentum distribution of the infalling gas.

We successfully test this new scenario using ab initio Large-scale Adaptive-mesh-refinement Omniscent Zoom-in (LAOZI) cosmological hydrodynamic simulations.

2. ARGUMENTS AGAINST INTERNAL REGULATION OF THE CENTRAL COMPONENTS
With the Advanced Camera for Surveys (ACS) Virgo Cluster Survey of early-type galaxies spanning four decades in mass, Côté et al. (2006) and Ferrarese et al. (2006) find a transition at $M_{R,0} = -20.5$, where the brighter galaxies lack resolved stellar nuclei and SMBHs dominate the CMO mass, while fainter ones have resolved stellar nuclei that dominate the CMO mass. Furthermore, the logarithm of the mean nucleus-to-galaxy luminosity ratio in fainter, nucleated galaxies, $-2.49 \pm 0.09 (\sigma = 0.59 \pm 0.15)$, is indistinguishable from that of the SMBH-to-bulge mass ratio, $-2.61 \pm 0.07 (\sigma = 0.45 \pm 0.09)$. A similar result is found by Wehner & Harris (2006) using a different data set. Turner et al. (2012) find an identical relation using early-type galaxies in the ACS Fornax Cluster Survey. We express the universal scaling relation between CMOs and bulges as

$$M_{\text{CMO}} = M_{\text{BH}} + M_{\text{NSC}} = \alpha M_{\text{BG}},$$

whereby with the transition between NSC and SMBH occurs at $M_B \sim -20.5$, or stellar mass $M_{\text{BG}} = (3 - 4) \times 10^{10} M_\odot$, and $\alpha = 2.5 \times 10^{-3}$ (Côté et al. 2006; Ferrarese et al. 2006; Wehner & Harris 2006; Turner et al. 2012). One may express
GAS SUPPLY TO NUCLEAR AND BULGE REGIONS

OVER COSMOLOGICAL TIMESCALES

Insights can be gained by asking the following question: can the feedback from SMBH and NSCs conspire to regulate the growth of the stellar bulge, i.e.,

\[ e_{\text{BH}} M_{\text{BH}} + e_{\text{NSC}} M_{\text{NSC}} + e_{\text{BG}} M_{\text{BG}} = f \sigma \theta M_{\text{BG}}. \]

The single power-law relation between \( M_{\text{CMO}} \) and \( M_{\text{BG}} \) across four decades in bulge mass can be understood only if the negative feedback per unit stellar mass of the NSC and of the SMBH are approximately the same, \( e_{\text{BH}} \approx e_{\text{NSC}} \), barring the unknown physical reason for the right-hand side of Equation (3)—the required amount of notional feedback to regulate the bulge growth—to change character abruptly at \( M_{\text{BG}} = M_{\text{BG}}^0 \).

Although having \( e_{\text{BH}} \approx e_{\text{NSC}} \) may be possible, it would render a negative answer to the question above (Equation (3)) as follows. In the momentum-driven regime, since the feedback from the nuclear cluster is subject to higher densities and shorter cooling timescales, it has diminished strength in comparison to that in the stellar bulge, i.e., \( e_{\text{BG}} > e_{\text{NSC}} \). In the energy-driven feedback scenario, \( e_{\text{BG}} = e_{\text{NSC}} \). Thus, since \( M_{\text{NSC}} \ll M_{\text{BG}} \), the supernova feedback from stars in the bulge would vastly exceed that from the NSC. This thus invalidates the statement that the NSC and SMBH provide the necessary feedback to regulate the growth of the bulge.

The only scenario left for the SMBH to regulate the bulge growth is to force \( e_{\text{NSC}} = 0 \) and assume the feedback per unit SMBH mass, while constant at \( M_{\text{BG}} > M_{\text{BG}}^0 \), to become negligible at about \( M_{\text{BG}} = M_{\text{BG}}^0 \). In both the momentum \((\beta = 1; \text{Ostriker et al. 2010})\) and energy feedback scenarios \((\beta = 2; \text{Faucher-Giguère and Quataert 2012})\), the amount of momentum or energy per unit SMBH mass, \( e_{\text{BH}} \), is ultimately proportional to the driving energy \((\approx M_{\text{BH}} c^2, \text{where } c \text{ is speed of light})\). Thus, there exists no known process to suddenly make \( e_{\text{BH}} \) drop to zero at some specific \( M_{\text{BH}} \), while being constant otherwise.

If negative feedback is needed to internally regulate the bulge, the only alternative left is stellar feedback from bulge stars themselves, i.e.,

\[ e_{\text{BG}} = f \sigma \theta. \]

Under the assumption that the feedback strength from stars per unit mass \( (e_{\text{BG}}) \) is constant, one obtains \( f \propto \sigma^{-\beta} \), which has the same dependence on \( \sigma \) as the predicted mass loading factors for both momentum \((\beta = 1)\) or energy \((\beta = 2)\) driven winds \((\text{e.g., Murray et al. 2005})\). Therefore, bulge self-regulation, if required, would be physically supportable and self-consistent.

If the bulge is self-regulated, then, under the assumption that \( e_{\text{NSC}} = e_{\text{BG}} \), NSC may also be self-regulated. The correlation between \( M_{\text{CMO}} \) and \( M_{\text{BG}} \) would then require that the mass loading factor for the SMBH is the same as for the NSC, i.e., \( e_{\text{BH}} = e_{\text{NSC}} \), which is a fine-tuned outcome. In the absence of inter-regulation between CMOs and bulges, the proportions of the amount of gas feeding the nuclear and bulge regions must be proportional to the observed \( M_{\text{CMO}}/M_{\text{BG}} \) ratio.

3. AN ALTERNATIVE SCENARIO: RATIONED COLD GAS SUPPLY TO NUCLEAR AND BULGE REGIONS OVER COSMOLOGICAL TIMESCALES

Our arguments in the previous section indicate that the observed \( M_{\text{CMO}}-M_{\text{BG}} \) correlation requires the same proportionality in the initial amounts of gas feeding the respective regions, averaged over the cosmological timescales. We test this scenario using direct cosmological simulations.

3.1. Simulation Characteristics

See Cen (2014) for a more detailed description of the ab initio LAOZI simulations. Briefly, we used the WMAP7-normalized (Komatsu et al. 2011) ΛCDM model: \( \Omega_m = 0.28, \Omega_b = 0.046, \Omega_{\Lambda} = 0.72, \sigma_8 = 0.82, H_0 = 100 \text{ km s}^{-1}\text{Mpc}^{-1} = 70 \text{ km s}^{-1}\text{Mpc}^{-1}, \text{and } n = 0.96. \) A zoom-in comoving box of \( 21 \times 24 \times 20 \text{ h}^{-3}\text{Mpc}^3 \) is embedded in a \( 120 \text{ h}^{-1}\text{Mpc} \) periodic box. The maximum resolution is better than \( 111 \text{ h}^{-1}\text{pc} \) (physical) at all times. Star formation follows the prescription of Cen & Ostriker (1992). Supernova feedback from star formation is modeled following Cen et al. (2005), with feedback energy being distributed into 27 local gas cells weighted by the specific volume of each cell, to mimic the process of supernova blastwave propagation to channel more energy into the less dense regions. We exclude AGN feedback in order to ascertain the lack of need for it.

3.2. Construction of Gas Feeding Histories of Simulated Galaxies

Galaxies are identified using the HOP algorithm (Eisenstein & Hut 1998) grouping stellar particles. Galaxy catalogs are constructed from \( z = 0.62 \) to \( z = 1.40 \) with an increment of \( \Delta z = 0.02 \) and from \( z = 1.40 \) to \( z = 6 \) with \( \Delta z = 0.05 \), having a temporal resolution of 30–150 Myr. For each galaxy at \( z = 0.62 \), a genealogical line is constructed up to \( z = 6 \), where the parent of each galaxy is identified with the one at the next higher redshift with the most overlap in stellar mass. At each redshift, we compute the amount \( (M_r) \) and mean specific angular momentum \( (J_r) \) of gas in the central 1 kpc region. To proceed, an ansatz is made: the gas mass with angular momentum lower than \( J_r \) is \( M_r \beta J_r/(1 + \beta J_r)^\nu \). We use \( \beta = 1 \), which corresponds to a Mestel (1963) disk of surface density \( \Sigma(r) \propto r^{-\nu} \). \( \beta = 1 \) is motivated by simulations of Hopkins & Quataert (2010, 2011) with resolutions as high as 0.1 pc. Figure 12 of Hopkins & Quataert (2010) shows that the evolved density runs of the gas disks, on average, follow the \( \Sigma(r) \propto r^{-\nu} \) profile from 0.1pc to 1kpc. In all of the six individual cases with significant gas inflow, shown in Figures (2) and (3) of Hopkins & Quataert (2011), the \( \Sigma(r) \propto r^{-\nu} \) profile provides an excellent fit. We compute the 1d stellar velocity dispersion \( \sigma \) within the effective radius for each galaxy in the simulation at any redshift and assume an SMBH of mass equal to \( M_{\text{BH}} = 10^8 M_\odot (\sigma/200 \text{ km s}^{-1})^4 \) (Tremaine et al. 2002).
The Bondi radius is

$$r_B = \frac{2GM_B}{3\sigma^2} = 7.2 \text{ pc} \left(\frac{\sigma}{200 \text{ km s}^{-1}}\right)^2,$$

(5)

and the specific angular momentum at $r_B$ is

$$J_B = \sqrt{2} r_B \sigma.$$

(6)

The gas landing within $r_0$ is assumed to accrete to the SMBH, where at $r > r_0$ the disk has a Toomre $Q$ parameter below unity and is hence consumed by star formation. Expressing various parameters by their fiducial values, we have

$$n_0 = 0.42 (\alpha/0.1)^{2/5} (E_{\text{E}}/0.1)^{-2/5} \left(\frac{M_{\text{BH}}}{10^8 M_\odot}\right)^{3/25} \times (Ma/0.1)^{1/25} (\kappa/\kappa_e)^{1/25} \text{ pc.}$$

(7)

(Goodman 2003, Equation (42)), where $\alpha$ is radiative efficiency, $E_{\text{E}}$ is luminosity in Eddington units, $Ma$ is Mach number of the viscous disk at $r_0$, and $\kappa$ and $\kappa_e$ opacity, and electron-scattering opacity, respectively. Hence, the feeding rate to the accretion disk that eventually accretes to the SMBH is

$$M_{\text{feed}} = M_e \left(\frac{r_0}{r_B}\right)^{1/2} \frac{J_B}{J_e} t_{\text{dyn}},$$

(8)

where the angular momentum at $r_0$ is $J_0 = (n_0/r_0)^{1/2} J_B$ for a Keplerian disk and $t_{\text{dyn}} = 1 \text{ kpc} / \sqrt{3} \sigma$ is the free-fall time at 1 kpc. For our analysis, we use

$$n_0 = 0.42 \left(\frac{M_{\text{BH}}}{10^8 M_\odot}\right)^{3/25} \text{ pc},$$

(9)

bearing in mind that uncertainties are at least on the order of unity. To see how uncertainty in $\beta$ affects results, we note that a 25% deviation in $\beta$ from unity causes $M_{\text{feed}}$ in Equation (8) to change by a factor of 2.7, which can be compensated by adjusting each of the parameters in Equation (7), except $M_{\text{BH}}$, by a factor of 2.5, appropriately.

### 3.3. Results

We define a ratio $R \equiv 500 M_{\text{feed}}/\text{SFR}$ (SFR is the star formation rate) such that if $R$ is about unity, the observed SMBH-to-bulge mass ratio of $\sim 0.2\%$ (e.g., Marconi & Hunt 2003; Häring & Rix 2004) would be borne out. Transformation from stellar disk(s) to a bulge is not addressed here. It is noted, however, that stellar disks formed from multiple gas inflows of inclined angles over the lifetime of a galaxy may be conducive to bulge formation. Note that SFR is computed directly during the simulation, whereas the SMBH accretion rate is computed in post-processing by evaluating Equation (8). Figure 1 shows histories of $M_{\text{feed}}$ (blue) and $R$ (red) for four random example galaxies. The most noticeable feature is that without any intentional tuning, $R$ hovers close to unity with fluctuations of the order of unity.

Figure 2 shows $R$ as a function of redshift. We see that $R$ increases with increasing redshift from $\sim 0.7$ at $z = 0.6$–1 to $\sim 1.5$ at $z = 3$–4 for galaxies with $10^{10.5–11} M_\odot$ (green), with similar trends for other mass ranges. We highlight three implications. First, the observed SMBH-to-bulge ratio is readily achievable in a cosmological setting, with a slight tendency for more massive galaxies to have higher $R$. This is due to the rationing of gas supply to the central regions of galaxies: a small amount of gas of the lowest angular momentum feeds the SMBH accretion disk, while the rest builds up the stellar bulge, with the demarcation line determined by the accretion disk stability condition. Note that our analysis is solely based on the angular momentum distribution of gas that has already landed in the central 1 kpc region. The frequency of gas inflow events into the central regions and the mass distribution of events are computed directly in our simulations. Second, $R$ increases with increasing redshift within a factor of $\sim 2$. The trend with redshift is expected in a cosmological context because both the frequency and strength of galaxy interactions increase with increasing redshift, yielding overall inflow gas of lower angular momentum, hence a larger $R$ at high redshift. Third, the smoothness of $R$ on cosmological timescales ($\gtrsim 100$ Myr) suggests that the dispersion of $R$ is modest, around the order of unity, at all redshifts, consistent with the dispersion of the observed correlation locally (note that the comparison is made between computed $M_{\text{feed}}$/SFR and observed $M_{\text{BH}}$/MBH). Future observations at high redshift may be able to test these predictions. Although $R$ is relatively smooth over cosmological timescales, the gas inflow rate varies up to an order of magnitude (Figure 1). The fluctuations in the inflow rate are caused by a variety of physical processes, including interactions between galaxies in close proximity, minor mergers, and occasional major mergers. We have not studied this in sufficient detail to ascertain whether secular processes play any major role.

Is SMBH accretion rate directly dictated by the feeding rate from galactic scales? Figure 3 shows the probability distribution of feeding rate in units of Eddington rate as a function of Eddington ratio. The Eddington ratio is based on the assumed $M_{\text{BH}}$ from the observed $M_{\text{BH}}$ – $\sigma$ relation. At $z \sim 0.6$, where comparisons with observations may be made, the computed distribution is steeper; the computed slope $\sim 3.3$ versus $\sim 0.60$ is observed. This indicates that accretion onto the SMBHs is “filtered” through physical processes operating on the accretion disk. This suggests that temporal correlation between AGN and star formation activities in individual galaxies below 30–150 Myr is expected to be weak, in excellent agreement with observations (e.g., Hickox et al. 2014). A comparison between the distribution of the feeding rate to the accretion disk (red curve) and that of the observed Eddington ratio (black dots) suggests that at $z \sim 0.6$ accretion disks around SMBHs spend most of the time accumulating gas, at a feeding rate below 1% Eddington ratio, and that the apparent power-law distribution of Eddington ratio may be a result of superposition of AGN internal light profiles that are universal in shape (i.e., a slope of $\sim 0.6$). We see that the computed feeding rate distribution shifts to the right $\sim 0.5$ dex per unit redshift, indicating that the duty cycle of luminous AGNs increases with redshift.

### 4. CONCLUSIONS

We have shown that, barring implausible physical fine-tuning, neither the CMOs—SMBHs nor NSCs—nor the stellar bulges can be regulated by blowing away the majority of gas that has already landed to explain the observed CMO–bulge relation. This leaves us with only one viable option. That is, the ratio of feeding rate to the nuclear region to that of the bulge is proportioned cosmologically.

We test this scenario using high-resolution, large-scale cosmological hydrodynamic simulations without AGN
Figure 1. Shows histories of the feeding rate $M_{\text{feed}}$ (blue) and $R \equiv 500 M_{\text{feed}}/\text{SFR}$ (red) for four random galaxies. The logarithm of the stellar mass for each galaxy at $z = 0.62$ is indicated at the top of each panel.

Figure 2. Median of $R$ as a function of redshift, separately for three stellar mass ranges $10^{9.5-10} M_\odot$ (red), $10^{10-10.5} M_\odot$ (blue), and $10^{10.5-11} M_\odot$ (green). The stellar mass is measured at the redshift in question. The vertical error bars indicate the interquartile range, whereas the horizontal error bars represent the redshift range of the bin. The red and blue points are horizontally slightly right-shifted for clarity of display. There are (659, 2214) galaxies with stellar mass in the range $10^{10.5-11} M_\odot$ for $z = (3 - 4, 0.62 - 1)$, respectively.
feedback. Our analysis finds a proportionality, $\sim 0.1\%–0.3\%$, between the feeding rate of very low angular momentum gas that can free fall to the subparsec region to accrete to the SMBH and the SFR in the galaxy. There is indication that this ratio increases with increasing redshift to within a factor of $\sim 2$, suggesting that the SMBH-to-bulge ratio is nearly redshift independent, with a modest increase with redshift. We predict that the duty cycle of luminous AGNs increases with redshift. While SMBHs and bulges are found to coevolve on $\gtrsim 30$–150 Myr timescales, there is indication that on smaller timescales, the SMBH accretion and star formation may be less or not correlated, which is likely due to variations of AGN activities on smaller timescales dictated by the physics of the accretion disk.

While our analysis disfavors internal regulation in terms of blowing gas away with the required proportionality, a ‘random’ internal regulation by blowing some gas away without the said proportionality is not ruled out and, in fact, may be common, manifested as galactic superwinds or AGN winds. We do not disfavor feedback processes that control the overall amount of cold gas supply, termed “global feedback.” Global feedback reflects the collective effects of stellar evolution (supernovae, winds, etc.) and SMBH accretion (winds, radio jets, etc.) as well as gravitational shock heating due to structure formation and photo-ionization heating, among others. They impact the thermodynamical state of the interstellar, circumgalactic, and intergalactic mediums. We emphasize that even if global feedback controls the overall cold gas supply and its temporal distribution on cosmological timescales, it is not responsible for the proportional growth of SMBHs and galaxies.

An implication is that the distinction between forming an NSC or SMBH may hinge on the existence of a massive enough initial black hole seed. Thus, the demarcation bulge mass of $M_{BG,0} = (3–4)\times 10^{10} M_\odot$ suggests that only the progenitors of the galaxies massive enough have formed massive black hole seeds at a high redshift, with less massive galaxies seeded by NSCs or neither. Subsequently, those with initial massive black hole seeds are able to accrete the infallen gas and grow to SMBHs over time, whereas those without massive black hole seeds turn the infallen gas in the nuclear regions into stars to grow the NSCs. Let us suppose that CMOs of initial mass $M_{CMO,init}$ created at a high redshift in dwarf galaxies have migrated to the centers of larger galaxies to serve as central seeds. The rationed gas supply would then yield the final $M_{CMO}/M_{BG} = (aM_{BG} + M_{CMO,init})/(M_{BG} + M_{CMO,init})$. Thus, for those galaxies lacking significant, subsequent growth of the CMO, i.e., $aM_{BG}$ is not much greater than $M_{CMO,init}$, the CMO–bulge mass scaling relation will be sublinear, which may explain the observed shallower scaling relation between NSCs and bulges at the low end of bulge mass (e.g., Erwin & Gadotti 2012; Leigh et al. 2012; Scott & Graham 2013; den Brok et al. 2014). Galaxies with a massive initial black hole seed may form an NSC as well, consistent with observations (e.g., González Delgado et al. 2008; Seth et al. 2008), although the stellar component in the vicinity of an SMBH may be altered by subsequent, additional processes, such as the inspiral of another SMBH (e.g., Milosavljević et al. 2002).

This study is related to Escala (2006, 2007), who studied gas accretion processes surrounding the SMBH; we explicitly avoid detailed accretion physics by focusing on the amount of mass that enters the “feeding” zone of the SMBH. This work reaches conclusions similar to those of Anglés-Alcázar et al. (2015) with respect to the $M_{BH} - M_{BG}$ ratio, with a contrasting difference on the role of feedback. While Anglés-Alcázar et al. (2015) requires that only a small fraction of the gas at subparsec scales is actually accreted by the SMBH, with the
rest lost to winds and outflows, we suggest that the gas disk beyond the Toomre unstable radius is instead consumed by star formation, without requiring blowing away most of the gas by the SMBH.

I am indebted to an anonymous referee for the most detailed, cogent, critical yet civilized reports, which have immensely helped improve the presentation and clarify numerous issues. I thank Dr. Guangtun Zhu for very helpful discussion. This work is supported in part by grant NASA NNX11AI23G.

REFERENCES

Adams, F. C., Graff, D. S., & Richstone, D. O. 2001, ApJL, 551, L31
Aird, J., Coil, A. L., Moustakas, J., et al. 2012, ApJ, 746, 90
Anglés-Alcázar, D., Özel, F., Davé, R., et al. 2015, ApJ, 800, 127
Cen, R. 2007, ApJL, 654, L37
Cen, R. 2014, ApJ, 781, 38
Cen, R., Nagamine, K., & Ostriker, J. P. 2005, ApJ, 635, 86
Colgate, S. A., Cen, R., Li, H., Currier, N., & Warren, M. S. 2003, ApJL, 598, L7
Côté, P., Piatek, S., Ferrarese, L., et al. 2006, ApJS, 165, 57
Croton, D. J., Springel, V., White, K., et al. 2006, MNRAS, 365, 11
den Brok, M., Peletier, R. F., Seth, A., et al. 2014, MNRAS, 445, 2385
Di Matteo, T., Springel, V., & Hernquist, L. 2005, Natur, 433, 604
Eisenstein, D. J., & Hut, P. 1998, ApJ, 498, 137
Erwin, P., & Gadotti, D. A. 2012, AdAst, 2012, 4
Escala, A. 2006, ApJL, 648, L13
Escala, A. 2007, ApJ, 671, 1264
Faucher-Giguère, C.-A., & Quataert, E. 2012, MNRAS, 425, 605
Ferrarese, L., Côté, P., Dalla Bontà, E., et al. 2006, ApJL, 644, L21
Ferrarese, L., & Merritt, D. 2000, ApJL, 539, L9
Gebhardt, K., Bender, R., Bower, G., et al. 2000, ApJL, 539, L13
González Delgado, R. M., Pérez, E., Cid Fernandes, R., & Schmitt, H. 2008, AJ, 135, 747
Goodman, J. 2003, MNRAS, 339, 937
Haring, N., & Rix, H. 2004, ApJL, 604, L89
Hickox, R. C., Mullaney, J. R., Alexander, D. M., et al. 2014, ApJ, 782, 9
Hopkins, P. F., Hernquist, L., Cox, T. J., et al. 2006, ApJ, 638, 1
Hopkins, P. F., & Quataert, E. 2010, MNRAS, 407, 1529
Hopkins, P. F., & Quataert, E. 2011, MNRAS, 415, 1027
Kauffmann, G., & Haehnelt, M. 2000, MNRAS, 311, 576
Komatsu, E., Smith, K. M., Dunkley, J., et al. 2011, ApJS, 192, 18
Leigh, N., Böker, T., & Knigge, C. 2012, MNRAS, 424, 2130
Magorrian, J., Tremaine, S., Richstone, D., et al. 1998, AJ, 115, 2285
Marconi, A., & Hunt, L. K. 2003, ApJL, 589, L21
Mestel, L. 1963, MNRAS, 126, 553
Milosavljević, M., Merritt, D., Rest, A., & van den Bosch, F. C. 2002, MNRAS, 331, L51
Murray, N., Quataert, E., & Thompson, T. A. 2005, ApJ, 618, 569
Ostriker, J. P. 2000, PhRvL, 84, 5258
Ostriker, J. P., Choi, E., Ciotti, L., Novak, G. S., & Proga, D. 2010, ApJ, 722, 642
Richstone, D., Ajhar, E. A., Bender, R., et al. 1998, Natur, 395, A14
Scott, N., & Graham, A. W. 2013, ApJL, 763, 76
Seth, A., Aguirre, M., Lee, D., & Basu-Zych, A. 2008, ApJ, 678, 116
Somerville, R. S., Hopkins, P. F., Cox, T. J., Robertson, B. E., & Hernquist, L. 2008, MNRAS, 391, 481
Tremaine, S., Gebhardt, K., Bender, R., et al. 2002, ApJ, 574, 740
Turner, M. L., Côté, P., Ferrarese, L., et al. 2012, ApJS, 203, 5
Wehner, E. H., & Harris, W. E. 2006, ApJL, 644, L17