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THE MASSIVE-BLACK-HOLE–VELOCITY-DISPERSION RELATION AND THE HALO BARYON FRACTION: A CASE FOR POSITIVE ACTIVE GALACTIC NUCLEUS FEEDBACK

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ABSTRACT

Force balance considerations put a limit on the rate of active galactic nucleus radiation momentum output, L/c, capable of driving galactic superwinds and reproducing the observed $M_{\rm BH}$–σ relation between black hole mass and spheroid velocity dispersion. We show that black holes cannot supply enough momentum in radiation to drive the gas out by pressure alone. Energy-driven winds give a $M_{\rm BH}$–σ scaling favored by a recent analysis but also fall short energetically once cooling is incorporated. We propose that outflow triggering of star formation by enhancing the intercloud medium turbulent pressure and squeezing clouds can supply the necessary boost and suggest possible tests of this hypothesis. Our hypothesis simultaneously can account for the observed halo baryon fraction.

Key words: galaxies: elliptical and lenticular, cD – galaxies: formation – galaxies: high-redshift – galaxies: nuclei – galaxies: starburst – quasars: general

Online-only material: color figures

1. INTRODUCTION

There is a consensus that the powerful active galactic nuclei (AGNs) play a crucial role in shaping the general properties of galaxies (e.g., Silk & Rees 1998; Croton et al. 2006; Silk & Norman 2009) and clusters of galaxies (e.g., Dalla Vecchia et al. 2004; Nusser et al. 2006; McNamara & Nulsen 2007). AGNs are powered by accretion onto supermassive black holes (SMBHs) believed to reside at the centers of most galaxies. An indication of the galaxy–black-hole connection is the remarkable correlation between the black hole mass, $M_{\rm BH}$, and the velocity dispersion, σ, of the spheroidal galactic components (e.g., Gültekin et al. 2009). Any successful model for galaxy formation must provide an explanation of this correlation. Self-regulated black hole growth offers a natural explanation for this relation (Silk & Rees 1998). Both radiation pressure and mechanical outflows deposit momentum into the protogalactic gas. If this results in a wind, force balance arguments (Fabian 1999; King 2003; Murray et al. 2005; Thompson et al. 2005; but see Soker 2009) lead to the conclusion that winds driven by pressure of radiation from a central black hole can suppress the collapse of gas and hence regulate the growth of the black hole. However, the available momentum is, we show, insufficient to give the required normalization of the $M_{\rm BH}$–σ scaling (Section 2).

The original self-regulation argument of Silk & Rees (1998) relied on energy balance: AGN activity heats the galactic gas reservoir above the virial temperature, generating galactic winds and eventually terminating gas accretion onto the black hole. However, energy-driven winds suffer strong radiative cooling losses: while the radiation heats the gas nearby the black hole, the gas expands but cools rapidly, making the process inefficient (Section 3). Our preferred solution is to introduce positive AGN feedback via triggered star formation. We argue that this simultaneously resolves three problems: the required order-of-magnitude boost in the $M_{\rm BH}$–σ scaling (Section 4), the enhanced specific star formation rate in massive galaxies (addressed elsewhere by Khochfar & Silk 2010), and the shortfall in the halo baryon fraction (Section 5).

2. CAN RADIATION MOMENTUM-DRIVEN WINDS EXPEL HALO GAS?

A luminosity $L/c = M_g g(r)$ balances the gravitational force applied on gas mass M_g by the dominant dark matter (DM) in a protogalactic halo. For isothermal DM and gas distributions, we get $g(r) = 2\sigma^2/r$ and $M_g(r) = f_g r^2 g(r)/G$ where σ is the velocity dispersion and f_g is the gas mass fraction. The force balance condition, with the simplifying assumption that the gas mass $M_g(r)$ lies entirely on the shell (Murray et al. 2005), r, yields a minimal luminosity

$$L = \frac{4 f_g c \sigma^4}{G} . \quad (1)$$

If we assume that L is proportional to $M_{\rm BH}$ as for the Eddington luminosity, $L_{\rm Edd} = 4\pi c G M_{\rm BH} m_p/\sigma_T$, this condition translates to

$$M_{\rm BH} = f_g \frac{\sigma_T}{m_p} \frac{\sigma^4}{\pi G^2} = 2\left(\frac{f_g}{0.1}\right) \sigma_2{}^4 \; 10^8 \, M_\odot , \quad (2)$$

very close to the observed $M_{\rm BH}$–σ relation $M_{\rm BH}t/\sigma_2{}^{4.24\pm0.41} = 10^{0.12\pm0.08}$ (Gültekin et al. 2009), where $M_{\rm BH}t = M_{\rm BH}/10^8 \, M_\odot$ and $\sigma_2 = \sigma/200 \, {\rm km \, s^{-1}}$.

These arguments do not take into account the lifetime of the AGN. The following consideration shows that black holes obeying the observed $M_{\rm BH}$–σ relation cannot generate enough energy in radiation in order to drive the gas out of the protogalactic potential well by radiation pressure. The work, $L(r_e - r)/c$, done by radiation pressure in moving the gas from r to r_e must be sufficient to bring the gas to the escape speed, $v_e(r_e) = \sqrt{-2\phi(r_e)}$, at r_e. Energy conservation then demands

$$\frac{L}{c}(r_e - r) > \frac{1}{2} M_g v_e^2(r) , \quad (3)$$

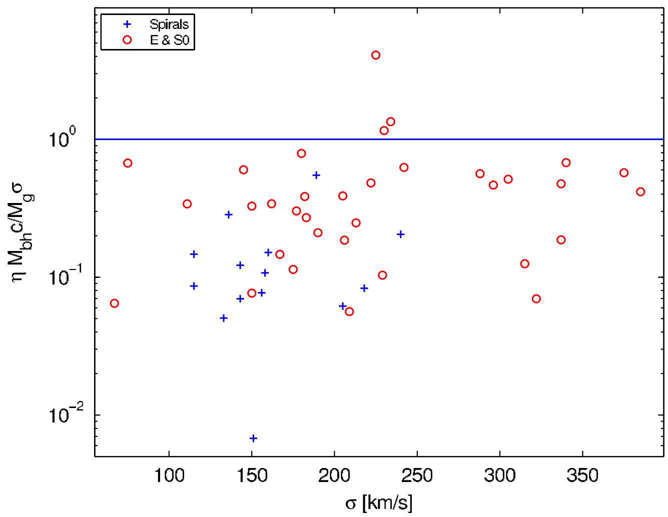

Figure 1. Plot of $\eta M_{\rm BH}c/(M_g\sigma c)$ (for $\eta = 0.1$) vs. σ from the sample of Gültekin et al. (2009). The horizontal line is $0.1\,M_{\rm BH} = M_g\sigma/c$. The black hole momentum falls short of the required momentum for most galaxies.

(A color version of this figure is available in the online journal.)

where $v_e(r) = \sqrt{-2\phi(r)}$ is the escape speed at r. The total energy radiated by the AGN during this process is $L\tau$ where $\tau = \int_r^{r_e} {\rm d}r/v(r) < (r - r_e)/v_e(r)$. Therefore, the energy radiated by the AGN must be greater than

$$E_m = L(r_e - r)/v_e(r) = \frac{c}{2}M_g v_e(r). \quad (4)$$

For an isothermal sphere truncated at the virial radius R_v, we have $V_e^2(r) = 4\sigma^2(1 + \ln\frac{R_v}{r})$ so that $E_m > M_g c\sigma$. The total energy $\eta M_{\rm BH}c^2$ ($\eta \sim 0.1$ is the efficiency factor) that could be extracted from the black hole must therefore satisfy

$$\eta M_{\rm BH}c > M_g\sigma\ , \quad (5)$$

as the condition for momentum-driven winds to be able to unbind galactic gas. The virial gas mass in a halo is $M_g = 7.3 \times 10^{11}\sigma_2{}^3(f_g/0.1)/h(z)\,M_\odot$, where $h(z) = H_0/H(z)$ and we have used $H_0 = 71\ {\rm km\,s^{-1}\,Mpc^{-1}}$. Therefore,

$$\eta M_{\rm BH}c > 5 \times 10^8\sigma_2{}^4(f_g/0.1)/h(z)\,M_\odot c. \quad (6)$$

Using the observed $M_{\rm BH}$–σ relation, we find that the black hole cannot unbind the gas by momentum even for $\sigma = 400\ {\rm km\,s^{-1}}$ at $z = 2$. The shortfall is about an order of magnitude at $z = 0$.

Complementary arguments are recently given by Anderson & Bregman (2010). These authors confirm the ubiquitous baryon fraction deficiency in galaxies. They compare baryon fractions in galaxies with varying bulge-to-disk-mass and demonstrate that the presence of an SMBH does not result in a reduced baryon fraction.

In Figure 1, we plot the ratio $0.1M_{\rm BH}c/(M_g\sigma)$ versus σ from the galaxy sample in Table 5 of Gültekin et al. (2009). As a proxy for M_g, the total gas mass to be ejected, we conservatively use the V-band luminosities of galaxies in the sample multiplied by a stellar mass-to-light ratio of 4. For the majority of galaxies in this sample, the maximum momentum $\eta M_{\rm BH}c$ falls short of $M_g\sigma$ by a factor of a few: half the sample falls short of the required threshold by a factor of at least 4, a quarter by a factor of 10. The figure also implies that the ratio depends weakly on the velocity dispersion.

Multiple scatterings can modulate the momentum delivered to the shell by the radiation but fail to resolve the momentum shortfall. Here is our reasoning. In the scattering case, force balance implies that

$$\rho g(r) = \kappa\rho\frac{L}{4\pi cr^2},$$

where ρ is the gas density. Assuming $g(r)$ is constant over the shell, we integrate this relation over the gas shell to give $gM_g = \tau L/c$, where τ is proportional to σ in the cosmological setting. Assuming L is proportional to $M_{\rm BH}$ and since gM_g is proportional to σ^4, this force balance relation implies that $M_{\rm BH} \propto \sigma^3$. Modulation by multiple scattering is therefore inconsistent with observations because τ scales with σ.

To obtain the correct relation $M_{\rm BH} \propto \sigma^4$, or possibly steeper, we consider a photon delivering its momentum in a single encounter with a gas particle. This is achieved if the gas surrounding the black hole is mostly neutral, which is plausible if the cooling time is short in the central regions. Predominance of molecular gas in the nuclear regions is inferred indirectly from dust, CO, and star formation observations. The optical depth for dust also scales with surface density (Thompson et al. 2005).

3. THE CASE AGAINST ENERGY-DRIVEN OUTFLOWS

Energy-driven outflows have been argued to give the wrong scaling relation (Silk & Rees 1998) for the observed $M_{\rm BH}$–σ relation, although a recent reanalysis favors the originally predicted $M_{\rm BH}$–σ^5 dependence (Graham et al. 2010). However, there is a more fundamental difficulty with energy-driven outflows. The gas initially cools by Compton scattering with the radiation emitted by the AGN (King 2003). This cooling indeed is important in the central region but lasts only as long as the AGN is active. Radiative cooling plays an important role in the AGN-galaxy interplay over longer timescales. Radiative cooling is extremely efficient in small halos ($\lesssim 5.10^{11}\,M_\odot$), where the cooling radius can even exceed the virial radius (Silk 1977; Rees & Ostriker 1977; White & Rees 1978). To explore the role of radiative cooling, we have simulated the feedback effects in spherical systems using a one-dimensional Lagrangian hydrodynamical code (see Nusser & Pointecouteau 2006 for numerical details.) In these simulations, the DM is assumed to reside in a static isothermal spherical halo truncated at the virial radius, $R_{\rm v}$, and the gravity of the gas is ignored. The gas is represented by 250 shells, which are equally spaced between $r = 0.1\,R_{\rm v}$ and $R_{\rm v}$, and are initially in hydrostatic equilibrium in the gravitational potential of the DM, with zero external pressure at $r = R_{\rm v}$. AGN feedback is introduced as heat added to the innermost shell over a timescale of 5×10^7 yr, which is shorter than the dynamical and the radiative cooling timescales. The equilibrium radiative cooling curve with metallicity of one-third solar as given in Sutherland & Dopita (1993) is adopted. Figure 2 shows the results from the simulations for two halos with $\sigma = 100\ {\rm km\,s^{-1}}$ and $\sigma = 300\ {\rm km\,s^{-1}}$. The explosion energy is taken to represent the AGN feedback and is equal to the gas potential energy in absolute value. The integrated AGN energy delivered to the system is set equal to the initial potential energy of the gas, about 1.4×59 erg and 3.4×61 erg for $\sigma = 100\ {\rm km\,s^{-1}}$ and $300\ {\rm km\,s^{-1}}$, respectively. The results in the left panel (no cooling case) demonstrate that for $\sigma = 100\ {\rm km\,s^{-1}}$ without cooling the gas is ejected from the system. For this smaller halo the radiated energy is so large that

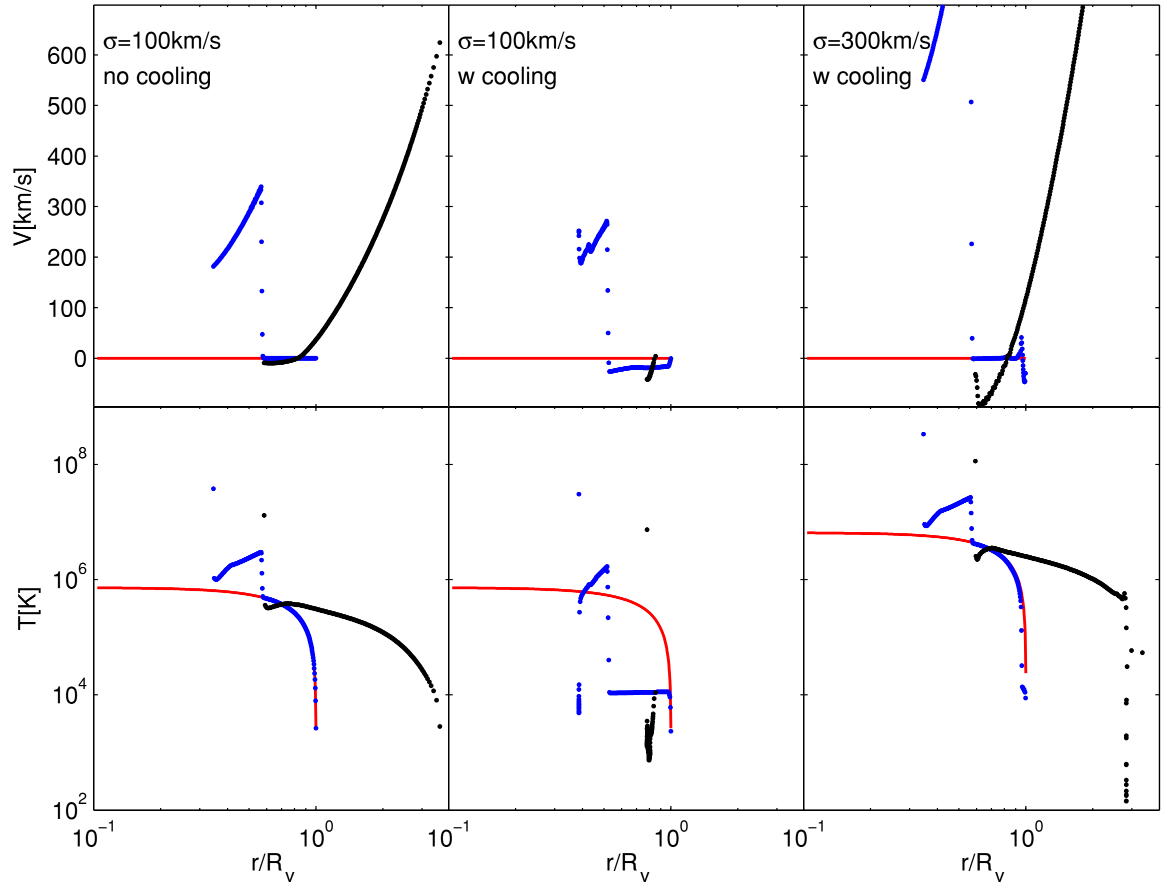

Figure 2. Effect of radiative cooling on the ejection of gas by a central explosion in isothermal halos. Left, middle, and right columns, respectively, correspond to $\sigma = 100$ km s^{-1} without cooling, $\sigma = 100$ km s^{-1} with radiative cooling, and $\sigma = 300$ km s^{-1} with cooling. Solid red lines represent the hydrostatic initial conditions. Blue dots represent the systems at some intermediate time. Black dots correspond to the final time of the runs at 1.3 Gyr after the explosion. Note that this one-dimensional simulation does not describe fragmentation of shells.

(A color version of this figure is available in the online journal.)

the total energy of the system at the final time is negative and the gas falls back onto the halo, as seen in the middle panel. Only for massive galaxies, $\sigma = 300$ km s^{-1}, right panel, does cooling play a lesser role, so that the feedback actually manages to unbind the gas out of the halo. For the effect of the cooling to be negligible, a self-regulating mechanism must operate so that the gas is rapidly ejected before cooling becomes important. But such a contrived mechanism will likely produce a complicated functional form for the $M_{\rm BH}$–σ relation which should reflect the dependence of the cooling curve on σ and the details of how the energy is ejected. Our discussion of the relevance of cooling demonstrates that momentum-driven outflows (Fabian 1999; King 2005) dominate over all mass scales of interest and, as we have shown, possibly give the correct scaling. Such flows are inevitable, as radiative cooling dominates over a longer timescale, especially in smaller systems. However, they cannot account for the observed normalization of the $M_{\rm BH}$–σ relation.

4. THE ROLE OF STAR FORMATION TRIGGERING BY AGN MOMENTUM-DRIVEN WINDS

If AGNs and supernovae (SNe) fail, admittedly for different reasons, to drive the required outflows, then we now argue that the combination may provide an ideal solution. For a black hole emitting at the Eddington luminosity, force balance yields $M_{\rm BH} \sim \sigma^4$, close to the observed scaling (see Equation (2)). The problem as we have seen is that the black hole cannot supply sufficient energy to suppress its own growth by expelling gas by radiation pressure, i.e., the black hole does not operate for long enough. The shortfall is a factor of a few. This conclusion is also sustained by recent observational data (e.g., Dunn et al. 2010). We propose here that a radiation momentum-driven wind triggers a starburst which joins forces with radiation to drive gas out of the protogalaxy. In this way, radiation momentum-driven winds, under certain physical assumptions, could yield a near $M_{\rm BH} \sim \sigma^4$ scaling although they are not solely responsible for gas expulsion.

If the triggered starburst is to aid in unbinding the gas by heating it above the halo's virial temperature, then $N_{\rm SN} E_{\rm SN} \approx 0.5\, M_g \sigma^2$, where $E_{\rm SN} \approx 10^{51}$ erg is the mechanical energy release per type-II SN (SNII) and $N_{\rm SN}$ is the number of SNII in the starburst. Further, the whole process of gas removal has to be short enough so that radiative cooling is not important. Since $M_g \sim \sigma^3$ and if we assume $N_{\rm SN} \sim M_{\rm BH}$, we get $M_{\rm BH} \sim \sigma^5$. This corresponds to the observed scaling in the energy-driven wind case and allows an acceptable normalization. Alternatively, to achieve a σ^4 scaling, our preferred model invokes considerations of momentum balance. The starburst must supply the "missing momentum" of a factor of a few of the black hole's $\eta M_{\rm BH} c$. The momentum boost works as follows. A supernova remnant (SNR) conserves energy until the swept-up shell mass decelerates to a velocity below $v_s \approx 400$ km s^{-1} (Cioffi et al. 1988), below which momentum is approximately conserved (in a uniform medium). The resulting inefficiency of SNR energy input is of order $v_{cl}/v_{\rm SN}$, where v_{cl} is the interstellar cloud velocity dispersion, and $v_{\rm SN} \approx E_{\rm SN}/[m_{\rm SN} v_s]$, where $E_{\rm SN} \approx 1.5 \times 10^{51}$ erg is the initial SN explosion energy and $m_{\rm SN} \approx 150\, M_\odot$ (for a standard initial mass function (IMF)) is the mass in stars required to form a supernova of type II. This inefficiency, of order a percent, is confirmed for more realistic conditions by numerical simulations of SN-driven galactic winds (Dubois & Teyssier 2008).

The momentum input is $E_{\rm SN}/v_s$ per supernova, and momentum balance for $N_{\rm SN}$ supernovae gives

$$N_{\rm SN} E_{\rm SN}/v_s = M_g \sigma. \quad (7)$$

Since the gas mass $M_g \overset{\propto}{\sim} \sigma^3$, this yields a boost satisfying the desired dependence on σ. The momentum boost $N_{\rm SN} E_{\rm SN}/v_s$ must be larger than $\eta M_{\rm BH} c$ by a factor of a few. To obtain this, we assume that the black hole growth rate is equal to the Eddington-limited accretion rate and that the star formation luminosity is equal to the Eddington luminosity. This is a reasonable approximation at zeroth order: in fact Netzer (2009) shows that there is a small tilt in the logarithmic relation for the star formation luminosity dependence on the luminous AGN that concern us here, with

$$L_* \overset{\propto}{\sim} L_{\rm bol}^{0.9},$$

where the bolometric luminosity is the sum of star formation and AGN luminosity. Our neglect of this tilt leaves the boost factor independent of mass and preserves the σ^4 dependence of the $M_{\rm BH}$–σ correlation. Therefore, we simply assume that the total star formation energy is $E_* = f_* \eta M_{\rm BH} c^2$, where f_* is a factor of order unity. The stellar mass associated with E_* is $M_* = E_*/(\epsilon_{\rm nuc} c^2) = f_*(\eta/0.1) 10^{10} M_{\rm BH} t$, where $\epsilon_{\rm nuc} \approx 10^{-3}$–$10^{-4}$, is the thermonuclear burning energy efficiency for a massive star. The associated mechanical energy produced by SNII in the starburst is

$$N_{\rm SN} E_{\rm SN}/v_s = \frac{f_* E_* E_{\rm SN}}{\epsilon_{\rm nuc} m_{\rm SN} c^2 v_s} = f_{\rm boost} \eta M_{\rm BH} c. \quad (8)$$

Also $N_{\rm SN} = M_*/m_{\rm SN}$, where $m_{\rm SN} \approx 100\, M_\odot$ is the mass in stars formed per SNII and is weakly IMF-dependent. The boost factor,

$$f_{\rm boost} = \frac{f_* E_{\rm SN}}{\epsilon_{\rm nuc} m_{\rm SN} c v_s}, \quad (9)$$

amounts to an order of magnitude for $f_* = 1$, $E_{\rm SN} = 10^{51}$ erg, $\epsilon_{\rm nuc} = 3.10^{-4}$, $m_{\rm SN} = 150\, M_\odot$ (expected for, e.g., a Chabrier IMF), and $v_s = 400\,{\rm km\,s^{-1}}$. Of course the question remaining is why the boost factor should be only weakly dependent on black hole mass. This requires more than a universal mass function of gas clouds since the AGN outflow pressure enters. But this might work, see Equation (85) in Silk & Norman (2009): the AGN-driven supersonic turbulence velocity dispersion is found to depend only logarithmically on AGN properties, as also does the porosity which controls turbulent pressure.

We now discuss the implications of our feedback models for further applications, notably to satellite abundances, intermediate-mass black holes (IMBHs), and the baryon fraction.

5. FEEDBACK, SATELLITE ABUNDANCES, AND BARYONIC FRACTION

AGN-triggered preheating is a plausible mechanism for reducing satellite abundances in galaxy groups or around massive early-type galaxies. Koposov et al. (2009) demonstrated that SN feedback plus reionization accounts for the luminosity function of the Milky Way Galaxy (MWG) and M31 dwarfs below $10^8\, M_\odot$. However, there are more intermediate mass galaxies (namely the Large Magellanic Cloud/Small Magellanic Cloud/M32/NGC205) in the MWG and M31 halos than are found in models tuned to fit the ultrafaint dwarf frequency. Models which fit the ultrafaint dwarfs are so efficient that they underproduce the massive dwarfs/intermediate mass galaxies. Conversely models tuned to fit the massive dwarfs have excessively inefficient feedback and overproduce the numbers of ultrafaint dwarfs. This problem seems to be common to all semi-analytical galaxy formation models (SAMs). Smith et al. (2009) confirm that SAMs fail to resolve this problem for the abundance of intermediate mass galaxies. This data set confirms that massive galaxies are overproduced in the models. Liu et al. (2010) also find that all SAMs overpredict the number of satellites by at least a factor of two in the mass range 10^9–$10^{10}\, M_\odot$.

AGNs are commonly introduced at early epochs to account for the black-hole–bulge correlation via the quasar feedback mode at early epochs. At late epochs, the AGN radio mode inhibits cooling of the dilute gas resulting from the earlier feedback process, keeps the gas hot, resolves the galaxy luminosity function bright end problem, and accounts for the red colors of massive early-type galaxies. We point out here that AGN feedback in the radio-quiet mode may also account for the suppression in numbers of dwarf satellite galaxies. Feedback from AGN in the host galaxies preheats the halo gas that otherwise would be captured by satellites. However, suppression of the formation of intermediate mass satellites of the Milky Way (MW), and more generally, late-type galaxies with small bulges may not be efficient because of the low masses of their central black holes. We have no solution to this problem, more generally associated with the large observed frequency of essentially bulgeless thin disks, other than to suggest patchy accretion of cold gas must play a role in thin disk formation at late epochs (but see Peebles & Nusser 2010). Once the potential well of a massive galaxy has developed, SNe do not eject gas, although they may drive interstellar turbulence and fountains. Gravitational heating does not work en route to forming the potential. All that is left is vigorous activity in the MW assembly stage. This phase may plausibly involve feedback from IMBHs, which are believed, at least by some, to be ubiquitous.

The hypothesis that IMBHs are formed generically during the hierarchical build-up of galaxies may possibly provide a radical solution to the baryon fraction problem via the momentum-driven outflows that we are invoking. Theoretical arguments suggest that one pathway toward building up the central SMBH is via mergers of IMBHs during the hierarchical merging evolution of DM halos. It is assumed that substructures develop IMBHs at early epochs, contemporaneously with first star formation. Simultaneously, another major problem is resolved, that of the baryon fraction, via preheating or ejection. This is seen to be low in low mass and in massive galaxies (McGaugh et al. 2010). If satellites form in a secondary manner, preheating reduces their baryon fraction. If satellites formed first, the quasar mode will sweep the gas out of the galaxy. This is achieved by a combination of AGN outflow momentum plus induced SN feedback. The gas subsequently stays out via the quiet mode of AGN feedback from the central host and other active galaxies.

Within the standard paradigm, the observed baryon fraction of the MWG with its small black hole is only explained if there are sufficient IMBHs in the satellites to drive out the baryons at early epochs (see Keselman et al. 2010 for an alternative non-standard explanations). For galaxies with massive spheroids, the central BH strips the satellites, reducing the number of IMBHs, but provides enough feedback to eject the baryons.

Baryons must be ejected in order to begin with the primordial baryon abundance, from galaxies of all mass scales, as well as galaxy groups. Only at clusters scales is the baryon fraction convergent. For dwarfs this is not a problem, but for typical galaxies, such as the MW, SN feedback cannot be responsible for baryon loss. Rather, the baryons are recycled via the halo. AGNs provide the only energy source capable of accounting for baryon ejection.

6. DISCUSSION

The primary aim of our paper is to highlight the scaling relation normalization problem for AGN feedback and to propose a possible solution involving AGN-triggered star formation. Positive feedback may have important ramifications for star formation at high redshift and is inevitably followed by gas outflows driven by both AGNs and SNe, along with concomitant quenching of star formation.

From the data plotted in Figure 1, the momentum boosting by the starburst is a factor of a few. This will naturally yield the dispersion in the relations given the nature of the boost, e.g., by BH outflow triggering of SNII. The points that lie low in the momentum condition had a larger boost, and this would lead to a prediction that the residuals in $M_{\mathrm{BH}}c$ versus $M_g\sigma$ should anticorrelate with SNII tracers in chemical evolution, e.g., the bulge α/Fe.

Small galaxies which formed stars before host galaxy AGN onset will survive. They should be seen as a bump in the galaxy luminosity function (GLF), analogously to what is seen in the MW (Koposov et al. 2009) and in the *K*-band GLF (Smith et al. 2009). These galaxies are distinguishable by being older and more metal-poor than their AGN-modulated successors which are primarily either low mass satellites or massive early-type galaxies. For the MW, the failure of the Koposov et al. (2009) model tuned to the numerous ultrafaint dwarfs to account for the admittedly sparse numbers of massive dwarfs is consistent with the lack of a large BH in our AGN feedback model. Feedback from IMBHs can resolve this problem. We suggest that the proposed IMBH in ωCen may be an example of a population of halo IMBHs that could have provided the additional feedback needed to both allow the LMC and similar dwarfs to form and not simultaneously overproduce the faint dwarfs. Such IMBHs could easily, during an active accretion phase, have produced enough momentum to have swept the residual gas out of the outer halo.

Globular clusters are plausibly the most visible surviving component of the first generation of substructure. That they might have a direct connection to IMBH is weakly supported by the possibility that one of the most massive globular clusters, ωCen, might contain an IMBH. Another hint of a connection with globular clusters may be present in the apparent correlation between black hole mass and mass of the host galaxy globular cluster system (Spitler & Forbes 2009). A variation on this relation has recently been found that relates black hole mass to the number of globular clusters (Burkert & Tremaine 2010). Numerical simulations find that the SMBH–σ scaling relation can be preserved by hierarchical mergers of IMBHs (Johansson et al. 2009). This lends support to the possibility that globular clusters may serve as a proxy both for IMBHs and for dwarf galaxies and therefore provide a possible witness to the required baryonic cleansing role of satellites by IMBHs in our model.

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