Environmental Dependence of Self-regulating Black Hole Feedback in Massive Galaxies

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Abstract

In the universe’s most massive galaxies, active galactic nucleus (AGN) feedback appears to limit star formation. The accumulation of cold gas near the central black hole fuels powerful AGN outbursts, keeping the ambient medium in a state marginally unstable to condensation and formation of cold gas clouds. However, the ability of that mechanism to self-regulate may depend on numerous environmental factors, including the depth of the potential well and the pressure of the surrounding circumgalactic medium (CGM). Here we present a suite of numerical simulations, with halo mass ranging from $2 \times 10^{12} M_\odot$ to $8 \times 10^{14} M_\odot$, exploring the dependence of AGN feedback on those environmental factors. We include the spatially extended mass and energy input from the massive galaxy’s old stellar population capable of sweeping gas out of the galaxy if the confining CGM pressure is sufficiently low. Our simulations show that this feedback mechanism is tightly self-regulating in a massive galaxy with a deep central potential and low CGM pressure, permitting only small amounts of multiphase gas to accumulate and allowing no star formation. In a similar-mass galaxy with shallower central potential and greater CGM pressure the feedback mechanism is more episodic, producing extended multiphase gas and allowing small rates of star formation ($\sim 0.1 \ M_\odot \ yr^{-1}$). At the low-mass end, the mechanism becomes implausibly explosive, perhaps because the CGM initially has no angular momentum, which would have reduced the amount of condensed gas capable of fueling feedback.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); Brightest cluster galaxies (181); Stellar feedback (1602); Active galaxies (17); Galaxy clusters (584); Supermassive black holes (1663); Circumgalactic medium (1879); Cooling flows (2028)

1. Introduction

X-ray observations during the past two decades have revolutionized the astronomical community’s understanding of how active galactic nuclei (AGNs) regulate cooling, condensation, and star formation at the centers of galaxy clusters. The high X-ray surface brightness of a cool-core cluster allows detection of cavities created in the hot gas by AGN outflows, along with measurements of their size, which show that AGN kinetic power is comparable to the radiative cooling rate of the cluster core (Churazov et al. 2001; McNamara & Nulsen 2007). Among galaxy clusters in the nearby universe, high-power radio AGNs, multiphase gas, and star formation are found only in those with low-entropy gas at their centers (Rafferty et al. 2006; Cavagnolo et al. 2008, 2009; Sun 2009; Hoffer et al. 2012; Rawle et al. 2012). These relationships indicate that AGN heating self-regulates through a feedback loop in which accretion of cold clouds condensing out of the hot medium strongly boosts AGN feedback power, thereby maintaining the core in a state marginally unstable to precipitation of cold clouds. The minimum ratio of gas cooling time ($t_{\text{cool}}$) to freefall time ($t_{\text{ff}}$) in such a self-regulating system tends to be in the range $10 < \min(t_{\text{cool}}/t_{\text{ff}}) < 20$ (Gaspari et al. 2012b; McCourt et al. 2012; Sharma et al. 2012; Li et al. 2015; Prasad et al. 2015, 2018; Voit et al. 2015a, 2015b, 2017). Many cool-core clusters observed with Chandra do indeed fall into this range (Voit et al. 2015b; Hogan et al. 2017), strongly supporting the hypothesis that AGN feedback in cluster cores is throttled by a transition to precipitation.

These findings raise an important question: Does precipitation-regulated AGN feedback also limit cooling and condensation of circumgalactic gas around smaller galaxies? The hot atmospheres of those galaxies tend to be harder to observe with X-ray telescopes, but preliminary investigations indicate that the AGN feedback loop observed in the universe’s largest galaxies may also limit the density of circumgalactic gas all the way down through Milky Way scales (Voit et al. 2018; Voit 2019). X-ray observations of massive ellipticals (Werner et al. 2012, 2014) show that the lower bound on $t_{\text{cool}}$ in the ambient medium tracks the $\min(t_{\text{cool}}/t_{\text{ff}}) \sim 10$ locus across two orders of magnitude in radius, from $\sim 20$ kpc down to $\sim 200$ pc (Voit et al. 2015b, 2015c, 2020). Also, the general features of precipitation-regulated star formation are consistent with several of the major scaling relations observed among galaxies (Voit et al. 2015a).

Several different channels can feed accretion of cold gas onto the central black hole. Numerical simulations show that cold gas can stream along cosmological dark matter filaments and accrete onto a halo’s central galaxy if those cold streams are not disrupted by a surrounding hot gaseous halo (Kereš et al. 2005; Dekel et al. 2009). In a galaxy cluster, radiative cooling of the halo’s hot gas can produce a central cooling flow (Fabian 1994; Pizzolato & Soker 2005). And in massive elliptical galaxies, accumulations of gas ejected from the old stellar population can also produce a central cooling flow (Mathews & Loewenstein 1986; Voit & Donahue 2011). All of
Numerical simulations demonstrate that bipolar AGN jets fueled by cold accretion can effectively quench star formation (Gaspari et al. 2012b, 2013; Li & Bryan 2014; Li et al. 2015; Prasad et al. 2015, 2018; Yang & Reynolds 2016; Meece et al. 2017). However, both the amount of cold gas that accumulates and its spatial distribution appear to depend on galactic environment. In galaxy clusters, $10^9-10^{11} M_\odot$ of molecular gas can accumulate, extending to tens of kiloparsecs from the center. Less molecular gas accumulates at the centers of smaller halos, and its spatial distribution appears to depend on the galaxy’s stellar velocity dispersion. In massive elliptical galaxies with central velocity dispersion $\sigma_v < 240$ km s$^{-1}$, the cold gas typically extends beyond the central 2 kpc, but it tends to be more centrally concentrated in galaxies with $\sigma_v > 240$ km s$^{-1}$, as long as they are not at the centers of galaxy clusters (Voit et al. 2015c, 2020). This relationship between $\sigma_v$ and the distribution of cold gas is intriguing, particularly in light of optical observations showing that quenching of star formation is more closely related to the stellar velocity dispersion of the central galaxy than to any other observable property (Wake et al. 2012; Bluck et al. 2016, 2020; Terrazas et al. 2016).

Here we present a suite of 3D hydrodynamic simulations motivated by the observed relationships between AGN feedback and galactic environment. The simulations were designed to investigate how bipolar AGN outflows fueled by cold accretion depend on halo mass, central velocity dispersion, and the pressure of the circumgalactic medium (CGM). Section 2 provides additional background on how the central stellar velocity dispersion is thought to influence the relationship between AGN feedback and CGM pressure. Section 3 describes the numerical setup for our simulations. Section 4 specifies the initial conditions for each numerical experiment. Section 5 presents the main results. Section 6 discusses the limitations of our simulations and their potential effects on the results. With those limitations in mind, Section 7 discusses our results, comparing them to theoretical models and prior simulations. Section 8 summarizes the paper’s main findings.

2. The Black Hole Feedback Valve

Spatially extended gas and energy input from the central galaxy’s old stellar population is an essential feature of the simulation suite we are presenting, because of how it links CGM pressure to AGN feedback. In a massive elliptical galaxy, energy input from Type Ia supernova (SN Ia) heating cannot by itself push ejected stellar gas out of the galaxy’s halo. Instead, that gas accumulates until its ambient density becomes great enough for radiative cooling to exceed SN Ia heating (Mathews & Loewenstein 1986; Ciotti et al. 1991; Binney & Tabor 1995). That process can take a few billion years. But eventually, the resulting cooling flow should make AGN feedback the dominant heating mechanism. It is therefore rather surprising that X-ray observations of nearby elliptical galaxies with $\sigma_v > 240$ km s$^{-1}$ are often consistent with models of steady subsonic outflows driven by SN Ia heating, at least within the central 1–10 kpc (Voit et al. 2015c, 2020).

In those models, AGN feedback and SN Ia heating play complementary roles. Feedback from the AGN is necessary to lift circumgalactic gas out of the galaxy’s potential well. However, lifting of the CGM lowers its pressure, causing conditions within the galaxy to change. As AGN feedback drives CGM pressure down, gas pressure and density within the galaxy also decline. AGN feedback therefore enables SN Ia heating to become more competitive with radiative cooling within the galaxy. Once the galaxy’s ambient gas density becomes low enough for SN Ia heating to exceed radiative cooling, SN Ia heating can limit the cooling flow that powers AGN feedback. Stellar mass and energy sources can therefore couple with AGN feedback to maintain a nearly steady state in which SN Ia heating slightly exceeds radiative cooling of gas within the galaxy.

Voit et al. (2020) refer to this tuning mechanism as a “black hole feedback valve.” It operates when the specific energy of gas ejected from the old stellar population ($\epsilon_{\text{SN}}$) is not much greater than the square of the galaxy’s stellar velocity dispersion ($\sigma_v^2$). In a steady outflow driven by SN Ia heating, the gradients of gas pressure, density, and entropy depend on the ratio $\epsilon_{\text{SN}}/\sigma_v^2$. As that ratio declines, the proportion of SN Ia energy needed to lift gas out of the galaxy becomes greater and the gradients of gas properties become larger.

A simple calculation in Voit et al. (2020) demonstrates that the tuning mechanism for a galaxy with a stellar population age of $\sim 10$ Gyr works best if $\sigma_v > 240$ km s$^{-1}$. At that limiting value of $\sigma_v$, the gradient of specific entropy $s$ approximately corresponds to $K \propto r^{-2/3}$, making the pressure and density gradients approximately $\propto 1/r$. For greater values of $\sigma_v$, the density gradient is steeper, causing radiative cooling to exceed SN Ia heating at small radii, even if SN Ia heating exceeds radiative cooling at larger radii. The result is a cooling flow at small radii ($< 1$ kpc) surrounded by a slow SN Ia-heated outflow extending to beyond $\sim 10$ kpc. Consequently, the CGM pressure confining the slow outflow determines the cooling flow rate at small radii. That coupling is what enables the mechanism to tune itself. It should inevitably shut down star formation by suppressing accumulation of extended multiphase gas in galaxies with a central velocity dispersion exceeding the critical limiting value, as long as the AGN produces enough power to lift the CGM out of the halo’s potential well.

One of this paper’s motivations was to see whether this black hole feedback valve mechanism would naturally arise in a 3D numerical simulation with the required properties. That is why $\sigma_v$ is an important environmental parameter and also why we pay particular attention to the relationship between SN Ia heating and radiative cooling. Our attempt to replicate the mechanism was only partially successful. Section 6 discusses some future improvements to simulations that may help to replicate the mechanism with greater realism.

3. Numerical Setup

We modified ENZO, an adaptive mesh refinement (AMR) code (Bryan et al. 2014; Brummel-Smith et al. 2019), to simulate AGN and stellar feedback in idealized galactic environments across a broad mass range. The masses of the simulated halos span the range $2 \times 10^{12} M_\odot \lesssim M_{200} \lesssim 8 \times 10^{14} M_\odot$, where $M_{200}$ is the mass contained within the radius $r_{200}$ encompassing a mean mass

$4$ This paper quantifies specific entropy in terms of the entropy index $K \equiv k T_\text{c}^{-2/3}$. 

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density 200 times the cosmological critical density. We solve the standard hydrodynamic equations in Cartesian coordinates, including radiative cooling, gravity, star formation, stellar feedback, and AGN feedback, along with mass and energy input from an old stellar population (see Section 3.4 for details). These simulations employ the piecewise parabolic method (PPM) with a Harten–Lax–van Leer-Contact Riemann solver.

### 3.1. Grids

The simulation domain is a (4 Mpc)$^3$ box with a 64$^3$ root grid and up to 10 levels of refinement. The central (128 kpc)$^3$ region enforces static regions of grid refinement ranging from level 6 to level 9, with the refinement level increasing toward the center. In the central (2 kpc)$^3$, the mesh is fixed to be at the highest level of refinement. This design ensures that the CGM is highly resolved at all times with a minimum cell size $\Delta l \approx 61$ pc and a maximum cell size $\Delta l < 1$ kpc.

#### 3.2. Environmental Parameters

The gravitational potentials in our simulations have three components, and they do not change with time. We use an NFW form (Navarro et al. 1997) for the dark matter halo, with mass density $\rho_{DM} \propto r^{-3}(1 + r/r_c)^{-2}$, where $r_c$ is the NFW scale radius and $c_{200} = r_{200}/r_c$ is a halo concentration parameter. For the central galaxy, we use a Hernquist profile (Hernquist 1990), with a stellar mass density $\rho_* \propto r^{-3}(1 + r/r_H)^{-3}$, where $r_H$ is the Hernquist scale radius. The potential of the central supermassive black hole of mass $M_{BH}$ follows a Paczynski–Witta form (Paczynski & Witta 1980).

Table 1 provides the parameter values for each model. Two of those models are based on particular galaxies. The multiphase galaxy (MPG) model is intended to resemble NGC 5044, which has a central stellar velocity dispersion $\sigma_\ast \approx 225$ km s$^{-1}$ and represents the population of massive elliptical galaxies with extended multiphase gas. The single-phase galaxy (SPG) model is intended to resemble NGC 4472, which has a central stellar velocity dispersion $\sigma_\ast \approx 282$ km s$^{-1}$ and represents the population of massive elliptical galaxies without much multiphase gas beyond the central kiloparsec. The brightest cluster galaxy (BCG) model is meant to represent the central region of a typical massive galaxy cluster. The smaller elliptical galaxy (SEG) model is designed to test how the AGN feedback mechanism used in the larger halos operates when the halo mass and central stellar velocity dispersion are reduced.

#### 3.3. Star Formation

A simulation cell forms a star particle if its gas satisfies several criteria based on the Cen & Ostriker (1992) prescription:

1. The baryon density must exceed a threshold density ($\sim$1 cm$^{-3}$).
2. The flow must be converging ($\nabla \cdot v_b < 0$).
3. The gas must be cold ($T < 1.1 \times 10^4$ K).
4. The gas mass of the cell ($m_\ast$) must exceed $10^3 M_\odot$.
5. The cooling time of the gas must be less than the dynamical time for that cell’s gas, $t_{dyn} = \sqrt{3\pi/(32G\rho_{gas})}$.

A star particle is then formed with mass $m_\ast = f_{\ast, eff} (\Delta t/t_{dyn}) m_\ast$, where the star formation efficiency parameter is set to $f_{\ast, eff} = 0.1$ in this simulation suite.

#### 3.4. Stellar Mass and Energy Input

The central galaxy’s stars heat the gas through two separate channels:

1. New stars forming during the course of the simulation produce Type II SNe (SNe II) that impart both thermal energy and momentum.
2. Old stars with the density distribution of the Hernquist potential (Section 3.2) add heat through SN Ia explosions and thermalization of stellar kinetic energy.

Feedback from stars formed during the simulation follows the prescription from Bryan et al. (2014). After a star particle of mass $m_\ast$ forms, a fraction $f_{SN_{\ast}}$ of its mass is added back to the cell, along with thermal energy $E_{SN} = f_{SN_{\ast}} m_\ast c^2$. Our simulations adopt the parameter values $f_{SN} = 1 \times 10^{-5}$ and $f_{SN_{\ast}} = 0.25$. The returned gas formally has a metallicity $f_{Z_{\ast}} = 0.02$, which can be used as a passive tracer but is not included in our radiative cooling calculations. This process starts immediately after the formation of the star particle and decays exponentially, with a time constant of 1 Myr.

SN Ia heating is modeled with steady, spherically symmetric injection of thermal energy into the simulation domain at a rate proportional to the stellar mass density. The total energy ejected from SN Ia explosions amounts to $10^{54}$ erg per SN Ia at a specific rate of $3 \times 10^{-14}$ SNe yr$^{-1} M_\odot^{-1}$, following Voit et al. (2015c). At this rate, an old stellar population of mass $\sim 10^{11} M_\odot$ adds $\sim10^{41}$ erg s$^{-1}$ of thermal energy. The old stellar population also injects kinetic energy as it sheds gas mass in the form of stellar winds and SN Ia explosions. Our simulations assume that this kinetic energy immediately thermalizes. We assume a specific gas ejection rate $\alpha_* = 10^{-19} s^{-1}$, such that the net ejected matter per unit time per unit volume is $\alpha_* \rho_\ast$.

To simplify the calculation of thermalized kinetic energy, we assume an isotropic 1D stellar velocity dispersion of 300 km s$^{-1}$ at all radii in all of our runs, following Wang...
et al. (2019). The difference between this uniform value of $\sigma_c$ and the actual one is inconsequential, because energy input from SN Ia heating is several times ($\geq 5$) greater than the kinetic energy injection in all cases.

### 3.5. AGN Feedback

AGN feedback is introduced into the simulation using a feedback zone attached to the AGN particle (Meece et al. 2017), which is always located at the geometric center of the halo. We drive AGN feedback in the form of a bipolar outflow by putting source terms for mass, momentum, and energy into the fluid equations as follows:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = S_p,
\]

\[
\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) = -\nabla P - \rho \nabla \phi + S_p
\]

\[
\frac{\partial (\rho e)}{\partial t} + \nabla \cdot (\rho e \mathbf{v}) = \rho \mathbf{v} \cdot \mathbf{g} - n_e n_i \lambda(T, Z) + S_c,
\]

where $S_p$, $\rho$, and $e$ are the density, momentum, and energy source terms, respectively. The specific energy $e$ includes kinetic energy, and the corresponding equation of state is $P = (\gamma - 1)\rho (e - v^2 / 2)$.

#### 3.5.1. Accretion and AGN Feedback Efficiency

The accretion rate $\dot{M}_{\text{acc}}$ onto the central supermassive black hole is calculated by assuming that all the cold gas ($T < 10^5$ K) within $r < 0.5$ kpc accretes onto the central black hole on a 1 Myr timescale. This mass accretion rate fuels AGN feedback at an energy output rate given by

\[
E_{\text{AGN}} = c_{\text{AGN}} \dot{M}_{\text{acc}} c^2,
\]

where $c$ is the speed of light and the feedback efficiency parameter $c_{\text{AGN}}$ is taken to be $10^{-4}$ for all our runs with AGN feedback. A cold gas mass equal to $\dot{M}_{\text{acc}} \Delta t$ is removed from the spherical accretion zone ($r < 0.5$ kpc) by subtraction of gas mass from each cell in that zone with a temperature below $10^5$ K, and the amount of gas mass subtracted from the cell is proportional to its total gas mass.

#### 3.5.2. Feedback Energy Deposition

The AGN output energy is partitioned into kinetic and thermal parts and introduced using the source terms described above. The source regions are cylinders of radius 0.5 kpc extending along the jet axis from $r = 0.5$ kpc to $r = 1$ kpc in each direction. Each jet therefore subtends 1 rad at $r = 1$ kpc.

In each cell of volume $\Delta V_{\text{cell}}$ within the source region of volume $V_{\text{jet}}$, the density source term is $S_p = \Delta m_{\text{cell}} / \Delta V_{\text{cell}}$, where

\[
\Delta m_{\text{cell}} = (\Delta V_{\text{cell}} / V_{\text{jet}}) \dot{M}_{\text{acc}} \Delta t
\]

and $\Delta t$ is the time step. Within the source region, the corresponding energy source term in each cell is $S_c = (\Delta e_{\text{cell}} + \Delta KE_{\text{cell}}) / V_{\text{cell}}$, where

\[
\Delta e_{\text{cell}} = (1 - f_{\text{kin}}) E_{\text{AGN}} \Delta t \cdot \frac{\Delta V_{\text{cell}}}{V_{\text{jet}}}
\]

\[
\Delta KE_{\text{cell}} = f_{\text{kin}} E_{\text{AGN}} \Delta t \cdot \frac{\Delta V_{\text{cell}}}{V_{\text{jet}}}
\]

For all our runs the ratio of kinetic to total AGN output energy is fixed at $f_{\text{kin}} = 0.9$.

The momentum source term in each cell is $S_p = \Delta p_{\text{cell}} / \Delta V_{\text{cell}}$, where

\[
\Delta p_{\text{cell}} = \Delta m_{\text{cell}} \sqrt{\frac{2 \Delta KE_{\text{cell}}}{\Delta m_{\text{cell}}}} \mathbf{\hat{n}}
\]

and $\mathbf{\hat{n}}$ is a unit vector pointing away from the origin along the jet injection axis.

### 4. Atmospheric Initial Conditions

All of the simulations in this paper begin with hydrostatic, single-phase galactic atmospheres having profiles of density, pressure, and specific entropy consistent with observations of nearby counterparts. Figure 1 shows the initial atmospheric properties for each simulation, along with the properties of the gravitational potentials and central galaxies outlined in Table 1. Solid lines in the top panels of Figure 1 show the total mass $M$ within the gravitational radius $r$ and the corresponding circular velocity, $v_c = \sqrt{GM(r) / r}$, while dashed lines show the same quantities for just the stellar mass component. Each initial entropy profile is modeled using the form

\[
K(r) = K_0 + K_{100} (r / 100 \text{ kpc})^\alpha
\]

(Cavagnolo et al. 2009). Table 2 gives the starting values of $K_0$, $K_{100}$, and $\alpha$ for each halo, which are based on observations by Cavagnolo et al. (2009) for the BCG model, Werner et al. (2012, 2014) for the MPG and SPG models, and Lakhchaura et al. (2018) and Babyk et al. (2018) for the SEG model.

The bottom left panel shows each galaxy’s initial entropy profile, and the bottom right panel shows the initial ratio of SN Ia heating to radiative cooling at each radius. Initial atmospheric pressure in the BCG and MPG is large enough that radiative cooling significantly exceeds SN Ia heating everywhere. In the initial state of the SPG, SN Ia heating nearly equals radiative cooling inside of $\sim 5$ kpc but is less significant at larger radii. However, the lower-pressure atmosphere of the SEG allows SN Ia heating to exceed radiative cooling within the central $\sim 5$ kpc. In all cases, the initial electron number density is set to a constant value $n_e = 5 \times 10^{-6} \text{ cm}^{-3}$ at an outer domain radius corresponding to $r_{200}$ in the three lower-mass halos and to $r_{200}$ in the most massive halo.

Throughout the simulation, atmospheric gas is allowed to cool to $10^3$ K using tabulated Sutherland & Dopita (1993) cooling functions with one-third solar metallicity for the BCG simulation and solar metallicity for all other runs.

### 5. Results

This section describes the key results from our simulations. We first examine how the atmospheres evolve without AGN feedback. In each case a cooling flow results, even if SN Ia heating initially exceeds radiative cooling. Then, we analyze how each atmosphere changes when AGN feedback is active. We find that the three more massive systems each settle into a self-regulated state within $\sim 1$ Gyr. The fluctuations in AGN feedback are larger in the two massive halos with greater CGM pressure and lower central velocity dispersion ($\sigma_v \approx 230 \text{ km s}^{-1}$), causing larger changes in core conditions and producing more multiphase gas over a larger region. In contrast, the massive halo with lower CGM pressure and greater central velocity dispersion ($\sigma_v \approx 280 \text{ km s}^{-1}$) quickly settles into a nearly steady self-regulating state in which SN Ia heating exceeds radiative cooling within the central $\sim 10$ kpc.
However, the lowest-mass halo \((M_{200} = 2 \times 10^{12} M_\odot)\) fails to self-regulate because AGN feedback becomes too explosive.

### 5.1. Simulations without AGN Feedback

To see how quickly star formation begins and what its rate would be without AGN feedback, we ran simulations of the three smaller halos with \(\epsilon_{\text{AGN}} = 0\). We did not perform a similar simulation of the BCG, because stellar feedback is obviously insufficient to limit star formation in such a massive halo. Figure 2 shows the resulting star formation rates as functions of time. Unsurprisingly, the MPG model begins to form stars almost immediately, because radiative cooling exceeds SN Ia heating at all radii. More than \(10^9 M_\odot\) of cold gas \((T < 10^5 \text{ K})\) accumulates by \(t \approx 250\) Myr, and star formation then proceeds at a steady rate \(\sim 25 M_\odot \text{ yr}^{-1}\). According to Voit (2011), the steady cooling flow rate associated with an entropy profile \(K(r) \propto r\) is

\[
\dot{M} = \frac{8\pi}{3} \mu m_p (kT)^2 \Lambda(T) \left(\frac{K}{r}\right)^{-3}
\]

in an isothermal potential. The asymptotic star formation rate observed in the MPG simulation without AGN feedback is therefore consistent with its initial entropy profile, which is \(K/r \approx 1 \text{ keV cm}^2 \text{kpc}^{-1}\) at \(\sim 10\) kpc.

More surprisingly, star formation also begins promptly in the SEG simulation without AGN feedback, even though SN Ia heating initially exceeds radiative cooling out to \(\sim 5\) kpc from the center. Figure 2 shows that star formation rises to \(\sim 8 M_\odot \text{ yr}^{-1}\) within the first 200 Myr. The amount of cold gas that accumulates during that same time period is comparable to the steady-state amount in the MPG simulation and is similar to the amount of hot gas that starts the simulation with a cooling time \(t_{\text{cool}} \lesssim 200\) Myr. The asymptotic star formation rate is again consistent with Equation (6), but with \(kT \sim 0.3\) keV.

Cooling and star formation begin within \(\sim 100\) Myr in the SEG model despite the central SN Ia heating, because the weight of its CGM prevents the gas ejected by old stars from leaving the galaxy. The initial gas-mass density at \(\sim 10^8\) Myr is

\[
\approx 24 M_\odot \text{ yr}^{-1} \left(\frac{kT}{1 \text{ keV}}\right)^2 \left[\frac{\Lambda(T)}{10^{-23} \text{ erg cm}^3 \text{s}^{-1}}\right] \times \left(\frac{K/r}{1 \text{ keV cm}^2 \text{kpc}^{-1}}\right)^3
\]

in an isothermal potential.
in uplift of low-entropy ambient gas that precipitates at \(\sim 10 \text{ kpc}\), forming new cold clouds. Those clouds then rain down toward the galaxy’s center, and during the next 50 Myr the ambient gas settles into a steady cooling flow.

Star formation requires more time to reach a steady state in the SPG simulation without AGN feedback. A brief burst of star formation happens at \(t \sim 50 \text{ Myr}\), because radiative cooling initially exceeds SN Ia heating everywhere. SN II feedback from that initial burst then lowers the central density, which allows SN Ia heating to exceed radiative cooling out to \(\sim 1 \text{ kpc}\). Star formation remains depressed for the next \(\sim 1.3 \text{ Gyr}\), while the central gas pressure gradually rises. The central pressure goes up during this period because SN Ia heating cannot push ejected stellar gas outward as fast as it accumulates and also because cooling of the overlying layers increases their weight. Eventually, the central gas density becomes great enough for radiative cooling to exceed SN Ia heating, and the resulting cooling flow boosts the star formation to a steady-state rate of \(\sim 3.5 \, M_\odot \text{ yr}^{-1}\) at \(t \sim 2.0 \text{ Gyr}\).

### 5.2. Massive Halos with AGN Feedback

In all of our simulations with AGN feedback, star formation is highly suppressed relative to the respective no-AGN counterparts (see Figure 2). However, condensation of the ambient medium couples with AGN feedback differently, depending on both the depth of the central potential well and the atmospheric pressure at larger radii. In the SPG simulation, coupling between condensation and AGN feedback is remarkably tight and maintains a nearly steady feedback-regulated state. In contrast, the MPG and BCG simulations exhibit greater feedback bursts. This section examines how these three massive halos self-regulate, while Section 5.3 looks at what happens in the SEG simulation, which fails to self-regulate.

#### 5.2.1. Radial Profiles

Figure 3 shows the median emissivity-weighted radial entropy profiles in the SPG, MPG, and BCG simulations with AGN feedback. A dashed magenta line indicates the initial entropy profile in each simulation. A solid red line traces the median profile for the entire period from 0.5 to 1.5 Gyr. Dark-gray shading shows the 20th–80th percentile range of the median entropy profile during that period, and light-gray shading shows the 1st–99th percentile range.

In each case, the median entropy profile shifts from its initial state into a different self-regulated state. The BCG entropy profile settles from a flat-entropy core into a self-regulated state with \(K \propto r^{2/3}\) in the central \(\sim 30 \text{ kpc}\). The MPG entropy profile rises to a self-regulated state with a mean entropy at \(< 10 \text{ kpc}\) several times greater than the initial state. The SPG

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**Table 2**

| Galaxy Model | Feedback Model | \(\epsilon_{\text{AGN}}\) | \(K(0)\) | \(K(0)\) | \(\alpha\) | Run Time | State at >1 Gyr |
|--------------|----------------|-----------------|----------|----------|--------|-----------|----------------|
| BCG          | AGN + stellar  | \(10^{-4}\)     | 15       | 230      | 1.1    | 2         | Episodically regulated core |
| MPG          | Stellar        | 0               | 1.3      | 150      | 1.05   | 1.5       | Cooling flow |
| MPG          | AGN + stellar  | \(10^{-4}\)     | 1.3      | 150      | 1.05   | 1.5       | Episodically regulated core |
| SPG          | Stellar        | 0               | 1.5      | 400      | 1.05   | 2         | Cooling > heating |
| SPG          | AGN + stellar  | \(10^{-4}\)     | 1.5      | 400      | 1.05   | 1.5       | Steadily regulated core |
| SEG          | Stellar        | 0               | 5        | 85       | 1.1    | 1.5       | Cooling flow |
| SEG          | AGN + stellar  | \(10^{-4}\)     | 5        | 85       | 1.1    | 1         | Overheated core |

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\(\rho \approx 5 \times 10^{-26} \text{ g cm}^{-3}\). At similar radii, the stellar mass density is \(\rho_\star \approx 10^{-22} \text{ g cm}^{-3}\), meaning that stellar ejecta can double the gas-mass density there on a timescale \(\rho(t) / (\nabla \nabla) \sim 150 \text{ Myr}\) if the gas cannot be pushed outward. Some of the gas is pushed outward, but not enough to prevent a buildup of gas within the central 5 kpc. Meanwhile, radiative cooling of gas just beyond \(< 5 \text{ kpc}\) produces an entropy inversion that makes the atmosphere convectively unstable and promotes thermal instability. Condensing gas clouds then sink to the center and initiate star formation. The resulting SN II explosions briefly suppress additional star formation but result in...
entropy profile also rises within the central ~10 kpc by a factor of ~2. However, the shading shows that tightly coupled feedback confines the SPG entropy profile to a much narrower range than in the BCG or MPG.

Comparing the data in Figure 3 with the simulation results reveals a significant discrepancy in the vicinity of 1 kpc, where specific entropy in the SPG and MPG simulations exceeds the observations by a factor of 2–3. In the middle panel showing the MPG simulation, some of that discrepancy might arise from a selection effect. The galaxies shown have particularly bright X-ray emission produced by atmospheres denser than average for their mass, meaning that they have lower-than-average specific entropy, but the data still remain within the fluctuation range of the simulation. However, the data in the SPG panel are well outside the fluctuation range of the SPG simulation. We therefore suspect that the entropy excess near 1 kpc results from a limitation of our simulation, which is the thickness of the AGN jet there. Section 6 discusses that limitation in more detail.

Figure 4 shows the median radial profiles of both \( t_{\text{cool}} \) (top panels) and the \( t_{\text{cool}}/t_{\text{fit}} \) ratio (bottom panels) during the same time period for the same three simulations. The left panels show that the SPG simulation self-regulates with \( \min(t_{\text{cool}}/t_{\text{fit}}) > 20 \) at >1 kpc and \( t_{\text{cool}} > 1 \) Gyr at 10 kpc. The middle panels show that the MPG simulation self-regulates with most of its time spent in the \( 0 < \min(t_{\text{cool}}/t_{\text{fit}}) < 20 \) range, with \( t_{\text{cool}} < 1 \) Gyr at 10 kpc. The right panels show that the BCG self-regulates with \( \min(t_{\text{cool}}/t_{\text{fit}}) \) fluctuating in and out of that range, also with \( t_{\text{cool}} < 1 \) Gyr at 10 kpc.

5.2.2. Self-regulation and SN Ia Heating

Self-regulation in these three simulations depends on how multiphase condensation couples AGN feedback with the state of the ambient medium. The top panels of Figure 5 show how injected jet power \( (P_{\text{jet}}) \) is related to X-ray luminosity \( (L_X) \) over the time period 0–1.5 Gyr. The X-ray luminosity is calculated in the “yt” package (Turk et al. 2011) using the “Cloudy” emission table for temperatures in the range of 0.5–7 keV with solar metallicity for all runs except the galaxy-cluster case, where a one-third solar metallicity emission table is used. After the initial AGN outburst of \( \sim 10^{43} \) erg s\(^{-1}\), the SPG settles into a nearly steady state with time-averaged AGN jet power that is similar to the X-ray luminosity from within the central 30 kpc. Frequent bursts fueled by fluctuations in the amount of cold gas within the central 0.5 kpc cause jet power to vary by a factor of \( \sim 10 \), but the power output remains steady when smoothed over timescales >100 Myr. However, the other two simulations experience much greater fluctuations in jet power.

In the MPG, AGN feedback is bimodal. The simulation starts with an outburst of jet power \( \sim 10^{44} \) erg s\(^{-1}\). Heat input from that outburst causes the galaxy’s atmosphere to expand, lowering its density and significantly reducing radiative cooling of the central 30 kpc. The AGN then enters a low-power state with \( P_{\text{jet}} \) fluctuating on a \( \sim 100 \) Myr timescale between \( \sim 10^{42} \) erg s\(^{-1}\) and a few times \( 10^{42} \) erg s\(^{-1}\). Meanwhile, the atmosphere’s X-ray luminosity climbs, because time-averaged AGN power is much less than \( L_X \) from within 30 kpc. Those radiative losses allow the weight of the CGM to compress the galactic atmosphere, gradually raising its density and pressure. The AGN remains in this low-power mode for \( \sim 800 \) Myr but then reverts back to a high-power state, similar to the initial one, for another \( \sim 200 \) Myr.

The BCG simulation remains in a state similar to the high-power mode of the MPG simulation most of the time and does not have a low-power mode. It is either near \( P_{\text{jet}} \approx 10^{44} \) erg s\(^{-1}\) or at \( P_{\text{jet}} < 10^{43} \) erg s\(^{-1}\). The state of extremely low power is likely to be artificial, resulting from the fact that our feedback algorithm sets AGN power to zero if there is no cold gas within the central 0.5 kpc. A more realistic model would include AGN power resulting from Bondi-like accretion of hot ambient gas, but jet power in that mode would be far too low to significantly affect the surrounding atmosphere.

The bottom panels of Figure 5 show how the mode of AGN feedback is related to the ratio of SN Ia heating to radiative cooling in the central few kiloparsecs. The radiative cooling for each radial shell is calculated \( \sim n_e n_p \Lambda(T) dV \), where \( dV \) is the volume of each radial shell and \( \Lambda(T) \) is the tabulated Sutherland–Dopita cooling function (Sutherland & Dopita 1993). Initially, radiative cooling in the SPG is slightly greater than SN Ia heating within ~5 kpc of the center. Cooling of that gas fuels a ~100 Myr burst of feedback that lowers the central gas density until SN Ia heating exceeds radiative cooling from ~0.5 to ~5 kpc. AGN feedback then enters the low-power mode, fueled only by cooling of gas within ~0.5 kpc of the center. And that mode is sufficient to keep the SPG in a steady state, for at least ~1.5 Gyr.

In the MPG, a larger initial burst of AGN power is needed to lower the atmosphere’s density because its confining CGM pressure is greater. However, SN Ia heating becomes comparable to radiative cooling at ~1 kpc by \( t \approx 300 \) Myr. The
simulation then settles into the low-power feedback mode for nearly 1 Gyr. During that time, AGN power is less steady than in the SPG because near equality of SN Ia heating and radiative cooling at $r < 3$ kpc allows larger condensation events to intermittently feed the AGN.

The BCG simulation, on the other hand, is in a cooling-dominated state everywhere during virtually the entire time period. AGN feedback cannot lower the atmosphere’s central density enough for SN Ia heating to equal radiative cooling. Therefore, the mode of self-regulation connects AGN feedback to large condensation events, which occur well outside of the central kiloparsec.

5.2.3. Cold Gas and Star Formation

In these simulations, central accumulation of cold gas couples atmospheric conditions with AGN feedback, while accumulations of cold gas at larger radii facilitate star formation. Figure 6 shows how the masses of cold gas ($M_{\text{cold}}$) and new stars change with time. In the SPG, the accumulations of cold gas are always small ($10^4$-$10^5$ $M_\odot$), and star formation is negligible. Note that the feedback algorithm described in Section 3.5.1 produces an AGN feedback power

$$\dot{E}_{\text{AGN}} = 6 \times 10^{42} \text{ erg s}^{-1} \left[ \frac{M_{\text{cold}}(<0.5 \text{ kpc})}{10^6 M_\odot} \right],$$

(7)
given $\epsilon_{\text{AGN}} = 10^{-4}$. The fluctuations in feedback power shown for this galaxy in Figure 5 are therefore consistent with the fluctuations in cold gas mass shown in Figure 6, as long as a large proportion of that gas ends up accreting onto the central black hole. Cold gas clouds forming through condensation are therefore consumed before they can form stars, linking the precipitation rate within 0.5 kpc directly to AGN feedback.

In the MPG, the mass of cold gas is $\sim 10^7$ $M_\odot$ in the high-power mode and $\sim 10^5$-$10^6$ $M_\odot$ in the low-power mode. Those amounts of cold gas are also largely consistent with the fluctuations in feedback power shown in Figure 5. Furthermore, the periods when cold gas extends beyond 1 kpc correlate with periods of greater star formation and AGN power. Feedback events that cause multiphase precipitation at larger radii therefore promote star formation in our simulations, because the cold gas clouds have time to form stars before sinking into the AGN accretion region in the central 0.5 kpc. Figure 2 shows that those star formation events briefly peak at a rate of $\sim 1 M_\odot$ yr$^{-1}$, but the accumulated stellar mass in Figure 6 implies a time-averaged rate of $\sim 1 M_\odot$ yr$^{-1}$ and a specific star formation rate of $\sim 10^{-12}$ yr$^{-1}$.

The BCG experiences several condensation events that push $M_{\text{cold}}$ up to $\sim 10^8$ $M_\odot$, producing surges of AGN power exceeding $10^{44}$ erg s$^{-1}$. Figure 5 shows that surges of this magnitude with a significant duty cycle are necessary to compensate for the radiative losses from within 30 kpc. Note that increasing the parameter $\epsilon_{\text{AGN}}$ and accretion time in our feedback algorithm would result in greater accumulation of cold gas, because balance between AGN feedback and radiative cooling would require less cold gas to be reprocessed within the accretion zone. The amount of star formation in this simulation is therefore contingent on the choice of $\epsilon_{\text{AGN}}$. For the choice $\epsilon_{\text{AGN}} = 10^{-4}$, the time-averaged star formation rate is $\sim 0.4 M_\odot$ yr$^{-1}$.

Figure 7 shows the maximum radial extent of cold gas ($T < 10^5$ K) as these different systems evolve. In the SPG simulation, cold gas remains concentrated within 1 kpc and
usually within 0.5 kpc, except during the initial outburst. In contrast, cold gas in the MPG generally extends beyond 1 kpc (sometimes as far as ~10 kpc), but cold gas in the BCG simulation tends to be less extended. Comparing cold gas radial extent to $P_{\text{jet}}$ in Figure 5 shows that cold gas becomes most extended following periods of strong AGN feedback, indicating that uplift of central gas promotes condensation at greater altitudes (Revaz et al. 2008; McNamara et al. 2016; Voit et al. 2017).

5.3. AGN Feedback in a Smaller Halo

Our AGN feedback simulation in a lower-mass halo (the SEG with $M_{200} = 2 \times 10^{12} M_\odot$) dramatically differs from the others. Figure 8 shows that the simulation produces a large AGN outburst and some star formation during the first 0.4 Gyr and then enters a state in which AGN feedback does not compensate for radiative losses. Instead, star formation and AGN power shut down, while $L_X$ and $M_{\text{cold}}$ steadily decline with time.

As in the SEG simulation without AGN feedback (see Section 5.1), the action begins at ~50 Myr when the central gas starts to condense. Those first cold clouds then trigger a self-exciting AGN feedback outburst. Uplift of low-entropy ambient gas simulates multiphase condensation that causes ~$5 \times 10^8 M_\odot$ of cold gas to precipitate by $t = 200$ Myr. Much of that cold gas falls radially back into the accretion zone (<0.5 kpc), boosting the jet power by a few times—up to ~$10^{44}$ erg s$^{-1}$, more than an order of magnitude greater than the radiative losses from the ambient medium ($L_X$). This powerful feedback event blows out much of the hot gas atmosphere but does not destroy the cold gas clouds, which can continue to rain back down in the accretion zone. The result is a decaying AGN feedback mode, in which intermittent accretion events produce smaller feedback outbursts that gradually lower the X-ray luminosity.

Figure 9 shows the evolution of entropy (left panel), $t_{\text{cool}}$ (middle panel), and $t_{\text{cool}}/t_{\text{ff}}$ (right panel) during the first 600 Myr of the SEG simulation with AGN feedback. During the first 300 Myr, strong AGN feedback pushes some of the low-entropy ambient gas from the central region to beyond ~10 kpc and heats the rest. The radiatively cooling outflow becomes most unstable to condensation near 10 kpc, where $t_{\text{cool}}/t_{\text{ff}}$ remains near unity for tens of megayears. That low-entropy gas then sinks inward and becomes the cold gas that sustains runaway feedback. A similar runaway does not happen in the more massive halos, because AGN feedback in those systems does not produce as much uplift and convection. Later in the simulation, we find $t_{\text{cool}}/t_{\text{ff}} < 10$ at ~100 kpc, but that gas condenses slowly because the cooling time there is several gigayears.

6. Limitations of Our Simulations

The primary limitation of our AGN feedback simulations is the thickness of the jets within the central few kiloparsecs, which is inherently a numerical limitation. In order to model a high-velocity AGN jet in a way that is numerically stable, we need to represent the outflow by modifying a “disk” of cells that is several cell widths in radius. At 1 kpc, the injected jets in our calculations subtend 1 rad, which is several times greater than the observed widths of powerful jets among the galaxies we are trying to model. For example, the angular width of the jet in NGC 4261 is ~0.2 rad at ~1 kpc (Nakahara et al. 2018). If our simulations had comparably narrow jets with the same kinetic power, they would likely drill more effectively through
Another limitation of our simulations is the initial lack of angular momentum in the galactic atmosphere. Injection of feedback energy produces turbulence that gives the cold clouds forming in that atmosphere some stochastic angular momentum, but often not enough angular momentum to prevent the clouds from sinking nearly radially down into the accretion zone at \( r < 0.5 \) kpc. In the three more massive halos (SPG, MPG, and BCG), the AGN feedback mechanism nevertheless manages to self-regulate, but in the SEG simulation it does not. We hypothesize that the initial lack of angular momentum is one of the factors that stymies self-regulation of the SEG, because it allows a self-exciting runaway of AGN feedback.

As mentioned in Section 5.3, uplift of ambient gas by the initial AGN feedback outburst in the SEG simulation stimulates condensation of \( >10^8 M_\odot \) of cold gas, much of which falls directly back into the accretion zone. Jet power therefore spikes to several times \( 10^{44} \) erg \( s^{-1} \) (see Equation (7)), dramatically heating and disrupting the CGM (see Figure 8). However, fewer of the cold clouds condensing out of the ambient medium would fall directly into the accretion zone if the atmosphere as a whole had greater net angular momentum. More of the condensing cold gas would then settle down in a torus around the central SMBH and get decoupled from the feedback cycle (Prasad et al. 2015). We are therefore preparing simulations to explore the role of angular momentum in moderating this AGN feedback mechanism in lower-mass galaxies.

### 7. Discussion

#### 7.1. Comparison with the Feedback Valve Model

The SPG and MPG simulations presented here were designed, in part, to test the “black hole feedback valve” mechanism proposed by Voit et al. (2015c, 2020) and summarized in Section 2. Qualitatively, the SPG and MPG simulations with AGN feedback do indeed self-regulate as envisioned, with AGN feedback tuning itself so that local radiative cooling is similar to SN Ia heating out to distances several kiloparsecs from the galaxy’s center. Figure 5 shows that the SPG simulation (\( \sigma_v \approx 280 \) km \( s^{-1} \)) begins with cooling exceeding heating everywhere and settles into a steady state with SN Ia heating exceeding radiative cooling from \( \sim 1 \) to \( \sim 5 \) kpc, as predicted by the feedback valve model for galaxies with \( \sigma_v > 240 \) km \( s^{-1} \). AGN feedback in this mode is fueled by cooling of gas within the central 0.5 kpc, while SN Ia heating sweeps much of the gas released by stars at larger radii out of the galaxy. This state can remain steady as long as AGN feedback prevents the confining CGM pressure from building up, and it succeeds for at least 1.5 Gyr because the time-

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Figure 6. Cold \( (T < 10^5 \) K) gas mass and accumulated stellar mass in the SPG (left panel), MPG (middle panel), and BCG (right panel) simulations with AGN feedback. Red lines show the amount of cold gas, and black lines show the amount outside the central kiloparsec. Dashed blue lines show the mass of the stars \((M_\star \text{ (young)})\) formed over the past 10 Myr. Solid blue lines show the cumulative mass of stars \((M_\star \text{ (accumulated)})\) formed during the course of the simulation. No stars form in the SPG simulation.

Figure 7. Radial extent of cold gas \((T < 10^5 \) K) in the AGN feedback simulations of the SPG (red line), MPG (blue line), and BCG (black line). In the SPG, cold gas almost always remains within 1 kpc. In all cases, cold gas reaches its maximum extent following high-power bursts of AGN feedback.

Figure 8. Temporal evolution of \( P_{\text{jet}} \) (red line), \( M_{\text{cold}} \) with 50 kpc (blue line), \( L_X \) within 50 kpc (dashed purple line), and star formation rate (black line) in the SEG simulation with AGN feedback. It does not self-regulate. Instead, a large feedback outburst reconfigures the entire hot gas atmosphere, leading to an extended period of gradual decline in \( P_{\text{jet}} \), \( M_{\text{cold}} \), and \( L_X \).

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the gas at \( \sim 1 \) kpc, coupling less strongly with the local ambient medium and thermalizing less of their kinetic energy there. We therefore hypothesize that the excess entropy at \( \sim 1 \) kpc in the SPG and MPG simulations, relative to the data in Figure 3, results from simulated jets that are too wide at that radius. We are currently testing that hypothesis with simulations that have narrower jets.
The center and boosts the AGN feedback power. The resulting runaway overheats the CGM, raising its entropy level to
then lifts low-entropy gas out of the central region and creates a thermally unstable entropy inversion at averaged jet power roughly matches radiative losses from the inner 30 kpc. However, we have not yet tested whether a galaxy with the SPG potential but a higher-pressure CGM (like the initial state of the MPG) tunes itself to this same steady state.

The MPG simulation ($\sigma_\text{e} \approx 230 \text{ km} \text{s}^{-1}$) also begins with cooling exceeding SN Ia heating everywhere. Kinetic AGN feedback with power $\sim 10^{44} \text{ erg} \text{ s}^{-1}$ then lowers the atmospheric density and abates when radiative cooling becomes similar to SN Ia heating within $\sim 3 \text{ kpc}$. The galaxy remains in this low-power state for nearly 1 Gyr but cannot sustain it because radiative losses from the inner 30 kpc exceed the jet power. The CGM pressure there remains high and gradually increases, preventing SN heating from sweeping ejected stellar gas out of the galaxy. Gas density and radiative cooling within the galaxy therefore both rise until the gas density reaches a ceiling imposed by the condition $\min(t_{\text{cool}}/t_{\text{ff}}) \approx 10$ (see Figure 4), at which precipitation of cold clouds inevitably triggers a large increase in feedback power. This second burst of feedback again lowers the central gas density until SN Ia heating is comparable to local radiative cooling (see the yellow line in the bottom middle panel of Figure 5). Consequently, the configuration of the ambient medium fluctuates but is bracketed by the state in which SN Ia heating exceeds radiative cooling and the state with $\min(t_{\text{cool}}/t_{\text{ff}}) \approx 10$, in alignment with the black hole feedback valve model for galaxies with $\sigma_\text{e} \approx 230 \text{ km} \text{s}^{-1}$.

Quantitatively, however, the simulations do not match the black hole feedback valve model in detail. One of the model’s key predictions is that the power-law slope of the entropy profile should exceed $K \propto r^{-2/3}$ at $r \sim 1$–10 kpc in galaxies with $\sigma_\text{e} > 240 \text{ km} \text{s}^{-1}$. The entropy profile at 1–10 kpc in our SPG simulation is much flatter than this prediction, which assumes that SN Ia heating exceeds AGN heating within the galaxy. While it is difficult to measure with precision how much of the heating at $\sim 1$ kpc is resulting from thermalization of jet energy, the excess entropy at that radius in the SPG simulation, relative to both the data and the analytical steady-flow models of Voit et al. (2020), suggests that the discrepancy results from excessive thermalization of jet kinetic energy at $\sim 1$ kpc in the simulation (see Section 6).

The predictions made in Voit et al. (2020) for galaxies like the SEG and BCG are less specific, but the results of our simulations of the SEG and BCG with AGN feedback generally conform to the model’s expectations. According to the model, a galaxy that does not supply enough feedback power to lift its CGM and alleviate the confining pressure should remain in a precipitation-limited state that self-regulates through multiphase condensation. The BCG simulation is consistent with that expectation of the model. For the SEG, the model predicts that multiphase circulation should be inevitable, because feedback overturns the atmosphere’s entropy gradient. And indeed, the feedback events observed in the simulation lift low-entropy ambient gas out of the center, catalyzing widespread condensation and production of cold gas, much of which falls back toward the center.

7.2. Comparisons with Prior Simulations

Several earlier numerical studies have explored the role of kinetic AGN feedback fueled by cold gas accretion in massive elliptical galaxies like the ones simulated in this paper. The efforts most closely related to our SPG and MPG simulations were published by Gaspari et al. (2011a, 2012a) and Wang et al. (2019). The ones most closely related to our BCG simulation were published by Gaspari et al. (2011b, 2012b), Li et al. (2015), Prasad et al. (2018), and Meece et al. (2017).

Gaspari et al. (2011a, 2011b, 2012a) performed the first suite of simulations to demonstrate that bipolar jets fueled by cold accretion can tune themselves to balance radiative cooling without overheating the central gas. Collectively, those three papers explored a range of halo mass similar to the range spanned by our SPG, MPG, and BCG models, but with substantially lower spatial resolution. Also, they adjusted their AGN feedback efficiency parameter, equivalent to our $\epsilon_{\text{AGN}}$, to optimize agreement with observations, finding the best results for $\epsilon_{\text{AGN}} \gtrsim 3 \times 10^{-4}$ in lower-mass halos and $\epsilon_{\text{AGN}} \gtrsim 5 \times 10^{-3}$ in cluster-scale halos. While mass and energy input from the old stellar population were included in these simulations, the role of the old stellar population in the overall feedback loop was not specifically analyzed.

The simulations of Wang et al. (2019), like ours, were motivated by the analysis of Voit et al. (2015c) and focused on distinguishing the roles of the central gravitational potential and the stellar mass and energy sources. Wang et al. (2019) performed two simulations similar to our SPG and MPG simulations with AGN feedback. The initial conditions in those simulations were not identical to ours but were inspired by the same two galaxies, with NGC 4472 representing single-phase elliptical galaxies and NGC 5044 representing MPGs. In alignment with our simulation results, Wang et al. (2019) found that AGN feedback in the galaxy similar to NGC 4472 maintained a relatively steady hot gas atmosphere with small amounts of centrally concentrated cold gas, while the same AGN feedback algorithm in the galaxy similar to NGC 5044 caused greater fluctuations in the hot gas atmosphere and
produced larger quantities of extended cold gas. Their general findings therefore also support the black hole feedback valve model.

However, the details of our simulation results differ from those of Wang et al. (2019). First, the median AGN power in Wang et al. (2019) is much greater, with jet power often rising above $10^{43}$ erg s$^{-1}$ in the SPG and rarely dropping below $10^{45}$ erg s$^{-1}$ in the MPG. Their large AGN feedback efficiency (equivalent to $\epsilon_{\text{AGN}} = 5 \times 10^{-3}$) allows the same amount of cold gas accretion to produce much more power, but that cannot be the whole explanation for the power difference, because self-regulation over a 1.5 Gyr period requires time-integrated heat input within the central 10–30 kpc (with $t_{\text{cool}} \lesssim 1.5$ Gyr) to balance radiative losses from the same region. Therefore, kinetic AGN power in Wang et al. (2019) must be thermalizing over a larger region, implying that it is propagating farther from the center. Second, specific entropy near $\sim 1$ kpc in the SPG of Wang et al. (2019) remains below 10 keV cm$^{-2}$ most of the time and is typically $\approx 5$ keV cm$^2$, in better agreement with observations of SPGs than our SPG simulation. In Section 6, we hypothesized that the excess entropy at $\sim 1$ kpc in our SPG simulation resulted from jets that were insufficiently narrow. And indeed, the jets implemented by Wang et al. (2019) are narrower, having a transverse momentum profile $\propto \exp(-r^2/2r_{\text{jet}}^2)$ with $r_{\text{jet}} = 183$ pc. With greater power and a smaller cross section, the jets in Wang et al. (2019) have a much greater momentum flux than ours and are capable of propagating to much greater distances, also accounting for why the simulations of Wang et al. (2019) require more AGN power to self-regulate.

Self-regulation of AGN feedback in our BCG simulation is broadly similar to what is observed in other simulations of its type (e.g., Gaspari et al. 2011b, 2012b; Li & Bryan 2014; Li et al. 2015; Prasad et al. 2015, 2018; Meece et al. 2017). Our BCG simulation’s typical value of $\min(t_{\text{cool}}/t_{\text{ff}})$ is greater than most, with a median ratio of $\sim 25$. In a future paper, we will show that the self-regulated $K(r)$ profile of our BCG simulation, which has an inner slope $K \propto r^{-2/3}$ (see Figure 3), is in excellent agreement with the observations of Hogan et al. (2017) and Babyk et al. (2018). However, unlike some of the other simulations, it produces less cold gas than is observed in cluster cores, and the cold gas it does produce rarely extends beyond 3 kpc.

The main reason for the lack of cold gas in our BCG simulation is the low feedback efficiency parameter and the small accretion time we have chosen. The small accretion time causes the cold gas forming within $r < 0.5$ kpc to be quickly removed from the simulation domain. This results in a high accretion rate, producing powerful AGN jets before much cold gas accumulates in the cluster core, despite the low AGN feedback efficiency. For $\epsilon_{\text{AGN}} = 10^{-4}$, the cold gas accretion rate required to sustain $10^{44}$ erg s$^{-1}$ of feedback power is $18M_\odot$ yr$^{-1}$. Our algorithm converts all of that cold gas to hot gas and expels it from the central region in a jet. Over the course of 1 Gyr, more than $10^{10} M_\odot$ would otherwise have accumulated, and much of it would likely have formed stars at a rate of $\sim 10 M_\odot$ yr$^{-1}$. In some of the other cluster-scale simulations (e.g., Gaspari et al. 2012b; Li & Bryan 2014; Prasad et al. 2015), much of the cold gas persists indefinitely in a torus orbiting outside of the accretion zone because of the stochastic angular momentum it gains during kinetic feedback bursts. Our simulation does not produce such a torus, and we will analyze what inhibits torus formation in a future paper.

8. Conclusions

The suite of simulations in this paper was designed to explore how a particular cold-fueled kinetic AGN feedback mechanism responds to differences in the surrounding potential well and initial atmospheric conditions. In halos ranging from galaxy-cluster scale ($8 \times 10^{14} M_\odot$), through galaxy-group scale ($4 \times 10^{13} M_\odot$), down to SEGs ($2 \times 10^{12} M_\odot$), we performed high-resolution 3D hydrodynamic simulations with radiative cooling, stellar feedback, and AGN feedback. We were particularly interested in testing the “black hole feedback valve” mechanism (see Section 2), which hypothesizes that coupling between AGN feedback and SN Ia heating tunes the confining CGM pressure so that SN Ia heating approximately equals radiative cooling within the galaxy.

The main results from those numerical experiments are as follows:

1. AGN feedback is necessary to quench star formation in all of our simulated galaxies.

2. The cold-fueled kinetic AGN feedback mechanism we implement becomes self-regulating within $\sim 200$ Myr in all three of the higher-mass halos ($M_{\text{200}} > 10^{13} M_\odot$).

3. AGN feedback in the two group-scale halos self-tunes to a state with SN Ia heating approximately equal to radiative cooling inside the central galaxy, and the nature of that self-regulated state depends on galactic velocity dispersion ($\sigma_v$) and confining CGM pressure. Those findings, which mirror those of Wang et al. (2019), are in general agreement with the black hole feedback valve hypothesis.

4. AGN feedback in our SPG simulation with $\sigma_v \approx 280$ km s$^{-1}$ maintains a nearly steady state, with time-averaged AGN power several times $10^{41}$ erg s$^{-1}$. Condensation of cold gas is focused within the central kiloparsec, as predicted by the black hole feedback valve model for galaxies with $\sigma_v > 240$ km s$^{-1}$. SN Ia heating exceeds radiative cooling at $\sim 1$–5 kpc and sweeps much of the gas ejected by stars out of the galaxy, while star formation is completely quenched. However, kinetic AGN feedback appears to overheat the region near $\sim 1$ kpc, producing excess entropy, relative to observations. We hypothesize that the bipolar jets implemented in our simulations overheat that region because they are too wide and therefore couple too strongly to the ambient gas there.

5. AGN feedback in our MPG simulation with $\sigma_v \approx 230$ km s$^{-1}$ is less steady, switching back and forth between a high-power state ($\sim 10^{44}$ erg s$^{-1}$) and a low-power state ($\sim 10^{42}$ erg s$^{-1}$). The high-power state is characterized by $\min(t_{\text{cool}}/t_{\text{ff}}) \sim 10$, extending to $\sim 15$ kpc, which allows precipitation of cold clouds out of the hot ambient medium to produce extended multiphase gas. AGN power fueled by accretion of the cold gas then heats the CGM and lowers its pressure until SN Ia heating approximately matches radiative cooling within the central few kiloparsecs. As that happens, the MPG simulation enters a low-power state but cannot maintain it, eventually reverting back to the high-power state with $\min(t_{\text{cool}}/t_{\text{ff}}) \sim 10$. These features are consistent with
the black hole feedback valve model for galaxies with $\sigma_\text{e} \lesssim 240 \text{ km s}^{-1}$.

6. CGM pressure in our BCG simulation is always great enough to ensure that radiative cooling exceeds SN Ia heating everywhere. It self-regulates with AGN power exceeding $10^{44} \text{ erg s}^{-1}$ for much of the simulation run time. However, not much cold gas accumulates compared to other similar galaxy-cluster simulations, probably because of our comparatively low feedback efficiency parameter ($\epsilon_{\text{AGN}} = 10^{-4}$).

7. In the SEG simulation, with $\sigma_\text{e} \approx 150 \text{ km s}^{-1}$, the cold-fueled kinetic feedback mechanism dramatically fails to self-regulate. As AGN feedback turns on and begins to lift the ambient gas, it stimulates copious multiphase condensation. Much of that cold gas then rains back down into the accretion region, causing an even stronger feedback response. This runaway of AGN feedback then overheats the ambient gas and blows out much of it out to $\sim 100 \text{ kpc}$. We suspect that the outcome of this simulation might have been different if the galaxy’s initial atmosphere had some net angular momentum. Much of the precipitating cold gas might then have avoided falling into the accretion zone and fueling the runaway response.

Future papers will present more detailed analyses of each of these simulations.

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Appendix

Section 6 of the paper discusses one of the key limitations of our simulations. The AGN jets we have implemented have a wide opening angle ($\theta \approx 1 \text{ rad}$), which generally results in thermalization of jet kinetic energy at smaller radii compared to narrower jets. That is a plausible reason for the excess entropy at $r < 2 \text{ kpc}$ for our SPG simulations, when compared to observations of single-phase elliptical galaxies (see the left panel of Figure 3).

After submission of the original manuscript, we initiated a systematic exploration of the effects of jet width on our simulated entropy profiles. Figure 10 shows some preliminary results. Its left panel shows our fiducial SPG simulation, with a jet opening angle of $1 \text{ rad}$ at the jet injection radius (1 kpc). The middle panel shows what happens when that opening angle is cut in half, to 0.5 rad. An entropy increase is seen at larger radii (10–20 kpc), confirming that the jets propagate farther and thermalize more of their kinetic energy at greater radii. The right panel shows what happens when the opening angle is further reduced to 0.25 rad. Significant entropy increases are then seen at even greater radii ($\sim 30 \text{ kpc}$). Also, in both simulations with narrower jets, entropy levels at 1–3 kpc are generally smaller than in the fiducial simulations and are in better agreement with the observed entropy profiles of SPGs.

We will present a more detailed analysis of the effects of changing jet width in a forthcoming paper that focuses exclusively on SPG and MPG simulations and explores their characteristics in greater detail.

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