THE EFFECTS OF X-RAY FEEDBACK FROM ACTIVE GALACTIC NUCLEI ON HOST GALAXY EVOLUTION

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Received 2010 October 5; accepted 2011 June 1; published 2011 August 9

ABSTRACT

Hydrodynamic simulations of galaxies with active galactic nuclei (AGNs) have typically employed feedback that is purely local, i.e., an injection of energy to the immediate neighborhood of the black hole (BH). We perform GADGET-2 simulations of massive elliptical galaxies with an additional feedback component: an observationally calibrated X-ray radiation field which emanates from the BH and heats gas out to large radii from the galaxy center. We find that including the heating and radiation pressure associated with this X-ray flux in our simulations enhances the effects which are commonly reported from AGN feedback. This new feedback model is twice as effective as traditional feedback at suppressing star formation, produces three times less star formation in the last 6 Gyr, and modestly lowers the final BH mass (30%). It is also significantly more effective than an X-ray background in reducing the number of satellite galaxies.

Key words: galaxies: elliptical and lenticular, cD – galaxies: formation – methods: numerical

Online-only material: color figures

1. INTRODUCTION

It has been well established that massive galaxies typically contain massive black holes (BHs) at their centers, and it is widely believed that these BHs, while in their so-called active galactic nucleus (AGN) phases, can have profound influence on the galaxies which host them (see Ferrarese & Ford 2005 for a comprehensive observational review). This influence is inferred from, among other observations, the correlation between the BH mass and the bulge mass of the host galaxy, which was first noticed by Kormendy & Richstone (1995) and studied extensively by various authors (see Magorrian et al. 1998, and has since been repeatedly confirmed (Haring & Rix 2004), as has the somewhat tighter relation between the BH mass and the host bulge’s velocity dispersion, discovered by Ferrarese & Merritt (2000) and Gebhardt et al. (2000). The inferred BH mass distribution has also been convincingly linked to the quasar luminosity function (Yu & Tremaine 2002).

Since the work of Silk & Rees (1998), the relationship between the AGN and host galaxy has generally been characterized as a process of feedback: the galaxy supplies gas to be accreted by the BH, which emits some fraction of the accreted mass as mechanical energy to the surroundings, some fraction via the broad-line winds, and some fraction as the radio jets. All these processes can heat the surrounding gas, and since gas which has been heated is less dense and thus accretes more slowly, the feedback process is described as “self-regulating” (i.e., a negative feedback loop).

Thus, there are two modes by which AGNs may give energy to their surroundings: the “mechanical” mode, where the AGN inflates local gas bubbles which expand through the interstellar and intergalactic media (ISM/IGM; Fabian et al. 2000; Churazov et al. 2002; Nulsen et al. 2005), and the “electromagnetic” mode, where photons from the AGN accretion region for which the neighboring gas has a low optical depth escape and directly interact with the rest of the ISM/IGM (Sazonov et al. 2005). Both of these modes may then interact with the surrounding galactic gas by either (or rather, both) of two mechanisms: energy based (i.e., heating; Silk & Rees 1998; Wyithe & Loeb 2003) or momentum based (i.e., pressure; Fabian et al. 2006; DeBuhr et al. 2011). Ciotti & Ostriker (2007) have included both mechanisms in their ongoing work. Thus, there are four conceptual components which feedback models may take into account: mechanical energy (a.k.a. bubbles), mechanical momentum (a.k.a. winds), electromagnetic energy (a.k.a. radiative heating), and electromagnetic momentum (a.k.a. radiation pressure). The relative importance of these components has been much debated among the authors just mentioned. A fifth component, the thin radio jets, emits comparable amounts of energy and momentum with the other modes, but these intense beams tend to drill through the galactic gas, depositing their energy in the IGM. This makes jets less relevant as a feedback method, unless they precess, or there is a relative velocity between the AGN and its environment, in which case significant heating of galactic gas could occur (Sternberg & Soker 2009; Soker 2009).

There has naturally been much interest in reproducing the AGN feedback process via numerical simulations. Springel et al. (2005) were among the first to do so using a high-resolution three-dimensional smoothed particle hydrodynamics (SPH) code. They found that including an accreting BH particle which returns energy to the surrounding gas reduces the fraction of baryons which form stars, and at late times (for massive galaxies) expels most of the remaining gas from the host, creating the classic “red and dead” elliptical. Since then, many more SPH simulations have been done, exploring various aspects of the AGN growth and feedback: Pelupessy et al. (2007), Khalatyan et al. (2008), Johansson et al. (2009a, 2009b), and McCarthy et al. (2010), to name a few.

However, even though it has been shown that the emitted spectrum of the average AGN power EF has a strong peak in the X-rays (∼30 keV; Sazonov et al. 2004), and moreover the ISM/IGM is known to be optically thin to hard X-rays...
in most cases (Morrison & McCammon 1983), all of the simulations just mentioned include only the mechanical-energy component of feedback. Some recent studies have included other components: Ostriker et al. (2010) examine the effect of mechanical-momentum feedback on the AGN growth in one-dimensional and two-dimensional simulations and find that including this component reduces the final BH mass by a factor of 100; DeBuhr et al. (2011) insert mechanical-momentum feedback into a three-dimensional SPH code (in fact the feedback was characterized as a radiation pressure, but only applied to the central 0.2 kpc of the galaxies, making it functionally mechanical) to examine its effects on the major mergers of disk galaxies, and found that with this component BHs self-regulate effectively during the mergers, but without driving large quantities of gas out of the galaxy altogether. Ciotti & Ostriker (2007), meanwhile, performed one-dimensional simulations with the full electromagnetic mode, considering the heating and radiation pressure from the AGN radiation, but without the mechanical mode. They studied the potential cooling flows of “recycled” gas from dying massive stars, and found that the electromagnetic mode alone was sufficient to drive out half of the incoming gas, with the BH only accreting 1% of the total (the remainder forming a starburst). However, until now no three-dimensional simulation has been performed with the electromagnetic mode included.

In Hambrick et al. (2009, hereafter Paper I), we examined the effect of various ionizing radiation backgrounds on the properties of massive elliptical galaxies. In Hambrick et al. (2010, hereafter Paper II), we examined the same backgrounds with respect to the small satellite galaxies of those massive ellipticals. Now we turn to a different source of ionizing radiation. It is the aim of this paper to present a first qualitative look at, and hint at quantitative results from, an AGN feedback model incorporating an X-ray electromagnetic mode.

This paper is organized as follows. In Section 2, we describe the numerical methods and parameters of our simulations, including the various AGN feedback models. In Section 3, we describe the results obtained from those simulations, in particular the effects of the different feedback models on the BHs themselves, on the gas and stars in the host galaxy and on the satellite galaxies. Section 4 is discussion and conclusion.

2. SIMULATIONS AND PARAMETERS

Our simulation code is GADGET-2, as in Paper II, with the only change being the addition of a BH and associated feedback. We use the UV background of Faucher-Giguère et al. (2009, which was designated as “FGUV” in Papers I and II). The simulation includes supernova thermal feedback but not winds or any stellar mass loss. It includes a simple prescription for metal-line cooling using cooling rates calculated by Cloudy (v07.02, last described in Ferland et al. 1998), which presumes photoionization and collisional equilibrium for the gas and metal atoms, and assumes 0.1 solar metallicity (note that our X-ray feedback code assumes solar metallicity, as discussed in Section 3.4). A self-consistent treatment of metallicity would increase the amount of cool gas available for accretion at later times and thus enhance the differences between our models. Our simulations do not include optical depth effects or radiative transfer, in particular the self-shielding of dense star-forming regions from the ionizing backgrounds, although those regions would be optically thin to X-rays regardless. As in Paper II, all simulations were performed with initially 100^3 each of SPH (i.e., baryon) particles and dark matter (DM) particles, with a gravitational softening length of 0.25 kpc for the gas and star particles and twice that for the DM particles. Gas and star particles have masses in the range 4–7 × 10^4 M☉ depending on the size of the box; the assumed cosmology is (ΩM, ΩΛ, Ωb/ΩM, σ8, h) = (0.3, 0.7, 0.2, 0.86, 0.65) as in Paper II.

The BH feedback works as follows. At z = 9 a single seed BH particle of mass 1.5 × 10^6 M☉ is created at the peak of minimum potential in the most massive progenitor halo. The seed mass is chosen to roughly follow the Magorrian relation for the galaxies at this redshift; the AGN behavior is not particularly sensitive to the seed mass (Hopkins et al. 2006). The BH grows at a modified Bondi–Hoyle–Littleton rate,

$$M_{\text{BH}} = \frac{4\pi \alpha_B (GM_{\text{BH}})^2 \rho}{(v_{\text{BH}} + c_s^2)^{3/2}},$$

(1)

where M_{BH} and v_{BH} are, respectively, the mass and speed (with respect to the surrounding gas) of the BH, and ρ and c_s are the density and sound speed of the gas in the SPH kernel centered on the BH (Springel et al. 2005; Di Matteo et al. 2005; Hopkins et al. 2006; Johansson et al. 2009b). The free dimensionless parameter α_B, which we choose to be 100, represents the fact that the gas density at the BH accretion radius is likely to be much higher than the average density in the local SPH kernel due to the limited resolution of the code (Hopkins et al. 2006; Booth & Schaye 2009). Future work could be done using the more realistic density-dependent accretion efficiency of Booth & Schaye (2009), which reduces to α = 1 for large accretion radii. The Bondi–Hoyle accretion is capped at the Eddington rate, M_{\text{edd}} = 4\pi Gm_{\text{BH}}/c_s^2$, where the BH notional mass as calculated from these accretion rates exceeds its true dynamical mass, the BH particle swallows nearby gas particles as needed to make up the difference. We enable artificial recentering of the BH particle on the potential minimum of the galaxy, since with our modest mass resolution dynamical friction is insufficient to keep the young BHs centered (though it is at late times, when the recentering has no effect).

We name our three feedback models: “BH,” “BHX,” and “BHXRP.” The “BH” model consists only of thermal energy deposited at each time step in the SPH kernel centered on the BH, in the amount of $E = \epsilon_\gamma \epsilon_T M_{\text{BH}} \sigma_T$, where $\epsilon_\gamma = 0.1$ is the overall radiative efficiency of the BH (Yu & Tremaine 2002) and $\epsilon_T$ the fraction of the radiation energy output which is assumed to be absorbed thermally by the local gas. Our choice of $\epsilon_T = 0.005$, together with our choice of $\alpha_B = 100$, is designed to produce a final (z = 0) BH mass roughly in line with the Magorrian relation for these galaxies. Note that our $\epsilon_T$ is 10 times smaller than the value used in other GADGET-2-based simulations (e.g., Springel et al. 2005; Johansson et al. 2009b), which is due to slightly different star formation criteria than the generic GADGET-2 (a lower density threshold for star formation, a star formation timescale which is shorter at low densities but constant at high densities and never shorter than the cooling time, and requiring the gas to fulfill a convergent flow criterion and the Bonnor–Ebert criterion to form stars), the upshot of which is that our stars form at somewhat lower gas densities, effectively lowering the BH accretion rate and thus its mass. Other simulations (e.g., Okamoto et al. 2008; Ostriker et al. 2010) have similarly used low efficiencies around $\epsilon_T = 0.01$—on the other hand, the OverWhelmingly Large Simulations (OWLS; Schaye et al. 2010), using a modified GADGET-3, find $\epsilon_T = 0.15$ to match the Magorrian relation,
though also finding that the value should be reduced for lower resolution (Booth & Schaye 2009). Furthermore, observational evidence suggests a value $\epsilon_T \approx 0.015$ (Moe et al. 2009), although since we neglect important processes like stellar mass loss and chemical evolution, our value (and others') for $\epsilon_T$ is constrained far more by the simulation than by physics. At any rate, we are primarily interested in the relative differences between the models with and without radiative feedback, which should not be significantly affected by the exact star formation prescription used. We call the mechanical-energy component “thermal” feedback for short to distinguish it from the X-ray feedback below. This energy component is of unspecified origin: if it is assumed to be the result of the broad-line wind, one should also include the momentum input (Ostriker et al. 2010), which has typically been neglected and will not be included here.

The “BHX” model has the same feedback component just discussed, with the same assumed efficiencies, but adds another: the electromagnetic-energy component of X-ray radiation from the AGN. This radiation is emitted from the location of the BH particle with a luminosity of $L_X = \epsilon_X \epsilon_{BH} c^2$, with a bolometric-to-X-ray conversion term $\epsilon_X$. This luminosity is converted to a flux at each gas particle simply by $F_X = L_X / 4\pi r^2$, with $r$ the distance of the particle from the BH, and the flux is converted to a heating rate for the gas using Equations (36)–(43) in Ciotti & Ostriker (2007, based on Sazonov et al. 2005), taking only terms which are dependent on the ionization parameter $\xi \propto F_X$. These equations are parameterized in terms of bolometric flux and implicitly assume $\epsilon_X \approx 0.04$ (as well as solar metallicity: see Section 3.4). We do not include radiative transfer/optical depth effects for this radiation (again, the ISM/IGM generally has a low optical depth to X-rays). Nor do we include a speed-of-light delay in propagation from the AGN across the box, but since our box’s high-resolution region is only 2 Mpc in radius and we are most interested in the central 30 kpc, the effects of no delay should be small.

The “BHXR” model adds a third component: electromagnetic momentum, the radiation pressure from this X-ray flux, by applying to each gas particle a radial force away from the BH particle equal to the X-ray heating rate at that time stepped divided by the speed of light $c$. We neglect the effect of dust, which dominates the opacity by several orders of magnitude at temperatures where it can exist ($T < 10^{3.5}$ K; Semenov et al. 2003), making this component perhaps an underestimate (although as discussed in Section 3.3 below, our heating rate may be overestimated due to metallicity effects).

As an additional point of comparison, we run a set of simulations designated “BH+X.” These have the same feedback mechanism as the regular BH runs but also include an X-ray background field (which the others do not). This field is identical to the “FGUV+X" model in Paper II; see that paper for details. Briefly, the field peaks in strength around $z = 2$ and falls off sharply at earlier and later times, to roughly emulate the observed quasar background (i.e., the X-ray heat due to galaxies other than the one being simulated). This model allows us to differentiate the effects of X-rays originating in the local AGN feedback from generic (spatially uniform) background radiation. We also compare it to a model with no AGN activity whatever, “No BH.”

We use three sets of initial conditions (IC) from Paper II that were designated galaxies/halos A, E, and M, and are so designated here as well. These are elliptical galaxies of virial mass $1-2 \times 10^{12} \, M_\odot$. As will be discussed below, all the galaxies gave the same qualitative results. As in Naab et al. (2007), Johansson et al. (2009c), and Paper I, we choose galaxy A as our fiducial case, noting any differences from the others where relevant.

Throughout the paper, all distances are physical except where noted, with assumed $h = 0.65$ as in Papers I and II.

3. RESULTS

3.1. Evolution of the Black Hole Mass

We first examine the effects of these various feedback mechanisms on the BH itself. It is well known that BHs are characterized only by mass, electric charge, and angular momentum (Bekenstein 1998), of which only the first is relevant here.

The top panel of Figure 1 shows the mass of the BH for our four feedback models with galaxy A. Also shown is a model where the thermal feedback efficiency parameter $\epsilon_T$ has been increased by a factor of 2 to 0.01 (notated as “BH, 2xFB” in the figure). We see that although the additional feedback present in the BHX and BHXR models reduces the final BH mass by 30% and 33%, respectively, compared to the BH model, these changes are significantly less than the factor of two reduction we see in the model with increased thermal feedback—and another model with thermal feedback increased 10 times has a lower BH mass by a factor of 25. This is because the thermal feedback directly affects only the immediately neighboring gas particles, which are the same particles used to calculate the BH local density and thus its accretion rate, whereas the X-ray feedback
predicts a BH mass of are consistent with the Magorrian relation for this galaxy, which primarily to more gas being available in the merger event at the BH+X model compared to thermal feedback. The X-ray affects all gas particles, thus making (as we will see) its effect on the host galaxy relatively stronger than its self-regulation effect, compared to thermal feedback.

On the other hand, the addition of an X-ray background in the BH+X model increases the final BH mass slightly (9%), due primarily to more gas being available in the merger event at $z = 0.7$. All the models except the enhanced thermal feedback model are consistent with the Magorrian relation for this galaxy, which predicts a BH mass of $\sim 2 \times 10^8 M_\odot$, depending on model, using the fit of Häring & Rix (2004)—since the galaxies are ellipticals, we approximate “bulge mass” as the stellar mass within three stellar half-mass radii ($\sim 18$ kpc) of the galaxy center. We note here that if the electromagnetic feedback (heating and radiation pressure) is used in the absence of any mechanical feedback, the BH becomes too large by three orders of magnitude: it seems that for our simulations the electromagnetic mode alone is insufficient for self-regulation. This differs from the result of Ciotti & Ostriker (2007), who found effective self-regulation using only electromagnetic feedback; we attribute the difference to their inclusion of dust opacity, which is certainly very important in AGN accretion regions (Scoville 2003), as well as their neglect of infalling satellite galaxies and IGM.

The lower panel of Figure 1 shows galaxy E, which is much the same as galaxy A, except for the major (1:1 mass ratio) merger event at $z \approx 1.5$ (10 Gyr ago), which drives a huge amount of gas to the BH and causes the mass to jump by a factor of $\sim 5$. Again in this case the BH+X model has the largest final mass (by $\sim 10\%$), thanks to the X-ray heating leaving more gas available to be accreted in the merger event. We also see that BHXRP accretes only half the gas of the other models at the moment of merger, making up the difference slowly over the next several Gyr; it seems that the radiation pressure is effective in blowing out the merging gas when X-ray heating and thermal feedback are not, consistent with DeBuhr et al. (2011). Otherwise, galaxies E and M are much the same as galaxy A, with BHX and BHXRP having lower BH masses by roughly 15% and 30%.

Another factor which we do not model here is the creation and mergers of BHs in subhalos. For simplicity, we have created only one BH, in the largest halo at $z = 9$ (which remains the largest halo until the present). While we do not expect the lack to change our results qualitatively, including AGN in satellites would reduce gas mass and star formation in those systems, leaving less gas and stellar mass to be accreted by the central galaxy in minor and major mergers. The effect would be especially strong on systems like galaxies E, with its nearly 1:1 merger.

Figure 2 shows absolute accretion rates for the same models with galaxy A. The rates are smoothed over 160 Myr for clarity; the BH accretion shows high variability over timescales as short as a few time steps ($\sim 100$ kyr). For the models with lower thermal feedback, the rate peaks near $1 M_\odot yr^{-1}$ around $4 \gtrsim z \gtrsim 3$, and slowly declines thereafter to a final value of $\sim 0.003 M_\odot yr^{-1}$, except for the peak around $z \approx 0.7$, which corresponds to a moderate (6.5 : 1) merger event for galaxy A. Of interest is the suppression of the accretion spike at $z = 3$ for the BHX model, and all three accretion spikes (at $z = 6, 4, 3$) by BHXRP; we see that these feedback modes are effective at self-regulation for very high accretion rates. Also of note is that for 4 Gyr after the merger BHXRP has more accretion than the other models by a factor of two (which will be significant in Section 3.3).

In the following subsections, we disregard the model with enhanced thermal feedback; in all cases its effects are the same or weaker than the plain BH model.

### 3.2. Impact on Gas

We now turn to the effects of the various BH models on the host galaxy. We expect our X-ray feedback to be quite effective at heating gas, and indeed it is. Figure 3 shows the temperature
distribution of all gas in the halo A box at $z = 3.2$ (during the epoch of peak star formation) and the present. At $z = 3.2$, the No BH model has the coldest gas, with a mean temperature of $6.4 \times 10^4$ K. Adding BH thermal feedback heats the gas 11% to $7.1 \times 10^4$ K, and adding an X-ray background heats it 24% more to $8.8 \times 10^4$ K. However, the two BHX models are more effective by another 9%, giving a mean gas temperature of roughly $9.6 \times 10^4$ K. At $z = 0$, the effect of feedback X-rays is more pronounced compared to a background: BHX and BHXRP, at a mean temperature of $3 \times 10^5$ K, are 25% hotter than BH+X, which in turn is only 14% hotter than BH and No BH. 

Figure 4 is the same as Figure 3, except that it shows only virialized gas: gas with a density more than 200 times the mean baryon density. Here the effect of the AGN feedback X-rays is more pronounced, as we would expect, since most of the virialized gas is near the central galaxy, where the AGN X-rays are strongest. At $z = 3.2$, the three models without X-ray feedback are all within 10% of each other in mean temperature at roughly $9 \times 10^4$ K, while BHX and BHXRP have mean temperatures of $1.6 \times 10^5$ K and $1.3 \times 10^5$ K, respectively, 40%–80% higher than the other models. At $z = 0$ the picture is even more extreme, BHX and BHXRP have $2.4 \times 10^{10} M_\odot$ and $3.0 \times 10^{10} M_\odot$, respectively, of virial X-ray gas $>10^5$ K, more than four times the amount that BH+X has, and six times the amount of the other models. Unlike the Warm–Hot Intergalactic Medium (WHIM), which is usually defined as $\rho < 100 \rho_b$ (Smith et al. 2010), this gas is dense enough to emit significant soft X-rays.

We estimate the (bremsstrahlung) X-ray luminosities of the various models via

$$L_X \propto \int \rho^2 \sqrt{T} dV$$

(Evrard 1990) for gas above $2 \times 10^6$ K over the virial volume (a 500 kpc radius), and find that all models have log $L_X \approx 38–39.5$, consistent with the gas luminosities found by Boroson et al. (2011) for 30 early-type galaxies of similar size. The differences between BH models is modest: averaged over the three ICs, the BH+X, BHX, and BHXRP models have increased luminosity by factors of 1.6, 2, and 3, respectively, compared with the models without X-rays. Adding BH feedback also increases the X-ray effective radius: only 33% of the total X-ray luminosity for No BH comes from outside the central 10 kpc, while 63% does for BH and BH+X, 68% for BHXRP, and 73% for BHX (again averaging the three ICs).

### 3.3. Impact on Stellar Mass

We naturally expect the hotter gas produced by the AGN X-ray feedback to reduce the production of stars. The upper panel of Figure 5 shows the star formation rate (SFR) over time for galaxy A, out to a radius of 30 kpc. We see only modest differences in the initial star formation peak (see below), but BH+X and BHXRP are both effective at suppressing late star formation: BHXRP has a lower SFR than the other models by 0.5 dex for the last 6 Gyr ($z < 0.6$), while BH+X suppresses the SFR by 0.8 dex for the last 1.5 Gyr ($z < 0.1$). BHXRP forms $3.4 \times 10^9 M_\odot$ of stars in the host galaxy after $z = 0.5$, and BH+X $3.6 \times 10^9 M_\odot$, which is less than half of the roughly $7.2 \times 10^9 M_\odot$ formed by the other models. The BH+X result is interesting in the context of Paper I, where the X-ray feedback produced a strong burst of late star formation, as gas that had been kept hot through the X-ray feedback peak at $z \approx 2$ finally cools and flows to the center of the galaxy to form stars (the so-called cooling flow). Here, a cooling flow seems to be forming around redshift of 0.3 (see the lower panel of Figure 5), but the AGN effectively shuts it off. The effect with BHXRP, meanwhile, is clearly related to its enhanced accretion rate after the merger event: we see from Figure 1 that BHXRP accretes less gas during a major merger, leaving a residual which forms a few central stars (see below), but more importantly powers extra
feedback for the next several Gyr, suppressing star formation at larger radii.

The lower panel of Figure 5 shows the SFR for galaxy A out to a radius of only 3 kpc (the three-dimensional stellar half-mass radius for the galaxy is the range 5–8 kpc). The results here are somewhat different: while all the models with BHs have no star formation at the present, BHX and BHXRP have nonzero star formation until roughly 1.5 Gyr ago, compared to 3 Gyr for the plain BH model (and 2.5 Gyr for BH+X). In terms of mass, BHX forms 1.7 \times 10^8 M_\odot in the central 3 kpc after z = 0.5, BHXRP 2.8 \times 10^8 M_\odot (the residual from the merger just discussed), which is 2–3 times more than the 1 \times 10^8 M_\odot formed by BH and BH+X, but still less than a tenth of the No BH model (3 \times 10^8 M_\odot). This is an expected result: as in Paper I, when X-ray heating is present, more gas is available at moderate and low redshift (z < 2) to be drawn to the galaxy’s center in major mergers and in cooling flows, and the AGN feedback, while eventually preventing most of this gas from forming stars, cannot do so immediately.

Table 1 shows the stellar mass of the host galaxy for the various models and ICs at three radii: 5 kpc, 30 kpc, and 2 Mpc (which is essentially the whole box). The total star formation in the box (Column 5) is suppressed slightly (5%) by the presence of the AGN, but the X-rays, whether from the AGN or the background, reduce the total stellar mass by 15%, three times as much. However, the background X-rays and the feedback X-rays cause their suppression differentially: as we see in Figure 6, which shows the star formation history of the entire box for the halo A runs, the two models with X-ray feedback suppress the star formation peak at 4 > z > 3, while BH+X is most effective at a somewhat lower redshift, 1.5 > z > 1. This clearly reflects the relative timing of the X-ray flux between the feedback and background sources, since the X-ray background peaks in intensity at \approx 2, while the X-rays from feedback peak when the BH accretion rate does, at 4 > z > 3. Thus, BHX can have a strong effect on the SFR peak—recall that in Figures 3 and 4 we saw that BHX has hotter gas than BH+X at z = 3.2—while later when the local AGN is less active, the X-ray background is relatively more effective. This difference in timing also produces a substantial effect on how the stellar mass is distributed, as we will see in the next subsection.

The stellar mass in the central galaxy (Column 4 of Table 1) is more or less as one would expect: thermal feedback and X-rays each reduce the stellar mass by a modest amount (~10%). To present the same results in a different way, the last column of Table 1 shows the baryon-conversion efficiency for the host galaxy, in this case identified using the Amiga Halo Finder (AHF; Knollmann & Knebe 2009). The value \epsilon_\star is defined as it was in Section 4.2 of Paper II, \epsilon_\star \equiv M_\star/M_{\text{Halo}}(\Omega_M/\Omega_\Lambda) \approx M_\star/M_{\text{Halo}} for our cosmology, where M_\star is the halo’s mass in star particles within 0.1 virial radii of the center and M_{\text{Halo}} its total virial mass. As discussed in Paper II, the absolute efficiencies for our models are all significantly higher than the value derived from Sloan Digital Sky Survey by Guo et al. (2010), ~0.2, but we are interested in the differences between the models. The two models with only thermal feedback reduce the efficiency by 0.035 from the No BH case, while adding the X-ray feedback (or an X-ray background in two of the three cases) reduces it by an additional 0.035. So our most effective model, BHXRP, reduces the baryon-conversion efficiency by 7% from No BH. This is only one fifth of the reduction which would be necessary to bring our simulations in line with Guo et al. (2010), but still a significant difference.

We find more unexpected effects in Column 3 of Table 1, which gives the stellar masses for the central 5 kpc of the galaxy. For galaxy A, the BHXRP model has almost 20% more mass than the other AGN models (though still 20% less than the No BH case), and 4% more than BHX at the 5 kpc radius. Once again this turns out to be associated with the SFR peak (though a small part comes from the extra late star formation discussed above): we see in the upper panel of Figure 7 that BHXRP has significantly more star formation in the peak at z \approx 4. This is clearly related to what we saw in the previous subsection: since BHXRP’s feedback is more effective at self regulation, it accretes less strongly at z \approx 4 and thus provides less heating to the surrounding gas, which can thus form more stars. That is, since the gas is pushed out by the feedback instead of merely being heated, the ability of the gas to form stars is less impaired.
Figure 7. Star formation rate over time for the various feedback models, considering stars within 5 kpc of the galaxy center for galaxy A (top panel) and galaxy E (bottom panel) at $z = 0$. In galaxy A, BHXRP allows significantly more central star formation than the other BH models, while the major merger in galaxy E causes more star formation for BHX.

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

even as the BH reduces its own growth rate. This effect is not robust, however: in the smaller galaxy M BHXRP has only barely more central mass than the other BH models, and in galaxy E it is BHX which has the most. But in this case BHX has slightly less stellar mass within 30 kpc than BHXRP, so it is only the central concentration which has been enhanced. This is related to the major merger event which galaxy E experiences: the extra residual gas from the early X-ray heating compared to the no-BHX models means more gas is driven to the center than BHXRP in galaxy E causes more star formation for BHX. This is slightly less stellar mass within 30 kpc than BHXRP, so it is BHX which has the most. But in this case BHX has slightly less stellar mass within 30 kpc than BHXRP, so it is only the central concentration which has been enhanced. This is related to the major merger event which galaxy E experiences: the extra residual gas from the early X-ray heating compared to the no-BHX models means more gas is driven to the center than BHXRP in galaxy E causes more star formation for BHX.

Figure 8 gives the radial mass distributions for galaxy A in the form of circular speeds. We would expect from Column 3 of Table 1. No BH has the highest peak speed and the steepest inner slope, with BH, BH+X, and BHX lower by about 25% in peak stellar circular speed and BHXRP in between. We can also parameterize the mass distribution with a “Faber–Jackson” statistic, $\sigma^4/M_*$, where $\sigma$ is the (three-dimensional) stellar velocity dispersion and $M_*$ is the stellar mass within some radius of the galaxy center. The BH+X model has the lowest $\sigma^4/M_*$, at about 25% in peak stellar circular speed and BHXRP in between. We can also parameterize the mass distribution with a “Faber–Jackson” statistic, $\sigma^4/M_*$, where $\sigma$ is the (three-dimensional) stellar velocity dispersion and $M_*$ is the stellar mass within some radius of the galaxy center. The BH+X model has the lowest $\sigma^4/M_*$, at about 25% in peak stellar circular speed and BHXRP in between.

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The results are given in Table 2: while the No BH and BH models agree within error with the values corresponding to their background from Paper II and BH+X has a modestly steeper slope likely related to the suppression of cooling flows), the BHX and BHXRP models indeed have an extreme effect on $\alpha_S$, flattening it well beyond the observed value of $\sim 1$ to $-0.44$ and $-0.55$, respectively. In Paper II we found that $\alpha$ increases as any heating is added: from $-1.6$ with no heating, to $-1.3$ with a UV background, to $-1.0$ with UV and supernova feedback, and to $-0.75$ with UV, feedback, and an X-ray background. As mentioned above, the timing of the X-rays seems to explain the difference between BH+X and BHX, since the BHX X-rays peak just before the epoch of primary star formation in low-mass galaxies (found in
Paper II to be $3 \gtrsim z \gtrsim 2$), while the X-ray background peaks toward the end of it and does not significantly suppress star formation until $z \approx 1.5$.

This result suggests that our X-ray feedback might be too strong: in fact, our formula converting X-ray flux to heating rate has a term (representing the photoionization heating and line and recombination cooling, Equation (A35) in Sazonov et al. 2005) which is linear in $Z/Z_{\odot}$—i.e., the metallicity as a fraction of solar—where solar metallicity is assumed (S. Sazonov 2010, private communication). Thus, since the metallicity of the ISM could be 0.1 $Z_{\odot}$ at early times, our heating rate could be too high by that factor. Moreover, the work of Hui & Haiman (2003) suggests that after reionization the equilibrium temperature of the IGM is roughly independent of the intensity of the radiation field, depending only on its spectrum, so our $r^{-2}$ attenuation factor may be less significant than we would naively think.

The results for $f M_{\text{crit}}$ are more modest. The quantity $f M_{\text{crit}}$ is defined in Paper II: in short, it represents the largest halo mass at which halos have an average star:DM mass ratio of less than half the global value (0.08). ($M_{\text{crit}}$ is the theoretically calculated virial mass whose escape velocity is equal to the sound speed of its gas at the epoch when it should be forming stars; the effective correction factor $f \approx 0.75$.) Here again, No BH, BH, and BH+X agree well with the values that Paper II gives from their ionizing background models. The X-ray background models have somewhat higher values, as we would expect from their flatter low-mass slopes.

4. DISCUSSION AND CONCLUSIONS

The effects of X-ray feedback from AGNs are manifold. We find that X-ray heating and radiation pressure are only moderately effective at self-regulation: they reduce the BH mass far less than increasing the thermal feedback efficiency does, primarily by suppressing bursts of Eddington-limited accretion at early times. The model with radiation pressure also accretes significantly less gas at the time of a major merger, instead accreting it more smoothly over the following several Gyr. The X-ray feedback produces a significant reduction in the host galaxy’s baryon-conversion efficiency compared to a traditional feedback model, but only slightly more than a model with traditional feedback and an X-ray background. We note however that our baryon-conversion efficiency remains well above the observationally derived value; though this problem is hardly unique to the present work it remains troublesome. On the other hand, less star formation would leave more gas available for AGN accretion, which would likely enhance the relative effect of electromagnetic feedback.

The enhanced accretion and associated feedback in the radiation-pressure model can also sustain a half-decade reduction in the SFR of the host galaxy for several Gyr after a major merger event, although the gas required for this extra feedback leads to more star formation in the central regions, which in turn can lead to enhanced central concentration. The AGN X-ray feedback also produces a significant mass of virialized, soft-X-ray-emitting gas at the present, which the X-ray background does not have (when ordinary AGN thermal feedback is present; in Paper I we found a significant mass in hot, dense gas for a model with X-ray background but no AGN feedback), which increases both the X-ray luminosity and the X-ray half-light radius. In a serendipitous final result, we find that this X-ray feedback is also much more effective than an X-ray background in suppressing small galaxies and thus flattening the low-mass slope of the galaxy mass spectrum, due to its feedback’s local origin making it effective at heating gas some 2–3 Gyr earlier than the background.

Since AGNs are known to emit X-rays through their host galaxies, we view this study as a vital first step toward a more complete model of AGN feedback. Moreover, since the X-ray luminosity of AGNs is relatively well constrained by observations (though not without intrinsic scatter), there is little need for a new free parameter to join the current $a_B$ and $\epsilon_T$ (modulo the effects of metallicity and dust). Thus, we hope that this “new” feedback mode will be employed in future SPH simulations of the AGN, since it is both undeniably present and, as we have shown, substantial in effect.

J.P.O. was supported by NSF grant AST-07-07505 and NASA grant NNX08AH31G. T.N. and P.H.J. acknowledge support by the DFG cluster of excellence “Origin and Structure of the Universe.”

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