Self-regulated black hole growth via momentum deposition in galaxy merger simulations

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ABSTRACT

We perform hydrodynamical simulations of major galaxy mergers using new methods for calculating the growth of massive black holes (BH) in galactic nuclei and their impact on the surrounding galaxy. We model BH growth by including a subgrid model for accretion produced by angular momentum transport on unresolved scales. The impact of the BH’s radiation on surrounding gas is approximated by depositing momentum into the ambient gas, which produces an outward force away from the BH. We argue that these phenomenological models for BH growth and feedback better approximate the interaction between the BH and dense gas in galaxies than previous models. We show that this physics leads to self-regulated BH growth: during the peak of activity, the accretion rate on to the BH is largely determined by the physics of BH feedback, not the subgrid accretion model. The BH significantly modifies the gas dynamics in the galactic nucleus ($\lesssim$300 pc), but does not generate large-scale galactic outflows. Integrated over an entire galaxy merger, BH feedback has little effect on the total number of stars formed, but is crucial for setting the BH’s mass.

Key words: galaxies: active – galaxies: formation.

1 INTRODUCTION

Modern theories of galaxy formation hold that strong feedback processes regulate star formation in galaxies across a wide range of masses. For more massive galaxies, stellar feedback processes appear to become less efficient and feedback from a central massive black hole (BH) begins to dominate. Feedback from an active galactic nucleus (AGN) has been invoked to account for many observational results in galaxy formation, including the $M_{\text{BH}}$–$M_\ast$ and $M_{\text{BH}}$–$\sigma$ relations and the suppression of star formation in elliptical galaxies (Silk & Rees 1998; King 2003; Di Matteo, Springel & Hernquist 2005; Murray, Quataert & Thompson 2005; Springel, Di Matteo & Hernquist 2005a; Hopkins et al. 2007).

Many recent studies developing numerical models for the effects of BHs on galactic scales have used broadly similar implementations of the uncertain physics of AGN fuelling and feedback (e.g. Kawata & Gibson 2005; Springel, Di Matteo & Hernquist 2005b; Johansson, Naab & Burkert 2009). It is e.g. often assumed that a BH of mass $M_{\text{BH}}$ accretes mass from the surrounding interstellar medium (ISM) at a rate proportional to the Bondi rate (Bondi 1952):

$$\dot{M}_{\text{Bondi}} = \frac{4\pi f G^2 M_{\text{BH}}^2 \rho}{c_s^3},$$

where $\rho$ is the surrounding gas density, $c_s$ is the sound speed and $f \sim 10–100$ takes into account the fact that the sphere of influence of the BH is not always resolved (Booth & Schaye 2009). Moreover, these same calculations assume that the BH’s impact on its host galaxy can be approximated by depositing thermal energy released by accretion back into the surrounding gas. There is, however, little detailed motivation or justification for either of these assumptions.

Equation (1) is only applicable when the gas fuelling the central BH has very little angular momentum. Otherwise, the transport of angular momentum regulates the accretion rate on to the central BH (e.g. Shlosman, Begelman & Frank 1990). It is generally believed that gas-rich disc galaxies are the progenitors of today’s $\gtrsim L^*$ ellipticals and, in particular, that mergers of gas-rich galaxies lead to luminous starbursts and the growth of central massive BHs (Sanders et al. 1988; Hopkins et al. 2005). Most of the gas in disc galaxies, merging galaxies, luminous starbursts (Downes & Solomon 1998; Tacconi et al. 2006) and nearby luminous AGN (Ho, Darling & Greene 2008) appears to reside in a rotationally supported disc. There is therefore no strong reason to believe that the spherically symmetric Bondi accretion rate is a reasonable estimate of the accretion rate on to a BH in gas-rich disc galaxies.

The energy generated by a central AGN can couple to its surroundings in a variety of ways, all of which may have a significant dynamical influence on gas in the host galaxy and in the surrounding intergalactic medium. For example, relativistic jets inject energy into intracluster plasma and may be the key mechanism
for suppressing cooling flows in galaxy clusters (McNamara & Nulsen 2007), although the details of how the energy in the jet couples to the surrounding plasma in a volume-filling way are not fully understood (Vernaleo & Reynolds 2006). On galactic scales, winds from an accretion disc around the BH may sweep up and drive gas out of galaxies (e.g. King 2003). And the AGN’s radiation can strongly impact the surrounding gas, both via Compton cooling/heating (e.g. Sazonov et al. 2005) and via the momentum imparted as ultraviolet (UV) radiation is absorbed by dust grains (Chang, Schiano & Wolfe 1987; Sanders et al. 1988).

The precise physical mechanism(s) responsible for AGN feedback is not fully understood, particularly on galactic scales. For this reason, it is useful to distinguish between two classes of models: energy and momentum injection. We believe that momentum injection, not energy injection, is likely the dominant form of feedback for the majority of the gas in a galaxy. In most circumstances, jets take the path of least resistance and travel relatively unimpeded out of a galaxy. Furthermore, while radiation from an AGN can, in principle, Compton heat the surrounding gas enough to unbind it, it can only do so for very low density gas. For example, for a BH radiating at $\sim 10^{46} \text{erg s}^{-1}$ with a typical quasar spectrum, only gas with $n < 1 \text{ cm}^{-3}$ can be heated to the Compton temperature within $\sim 100 \text{ pc}$. However, the mean gas densities in the central $\sim 10 \text{ pc}$ of ultraluminous infrared (IR) galaxies are $\sim 10^3 \text{ cm}^{-3}$ (Downes & Solomon 1998). At these densities, the cooling time of the gas is very short and the gas is unable to retain any injected energy. Thus if the radiation from a BH strongly modifies the dynamics of the gas in its immediate vicinity, it must be via the force exerted when the radiation is absorbed.

Given the uncertainties in the physics of BH accretion and feedback, it is important to explore a range of models for the impact of BHs on galaxy formation. Towards this end, we have carried out numerical simulations of major galaxy mergers, qualitatively taking into account the physics of accretion induced by angular momentum transport and AGN feedback by momentum injection (radiation pressure). Our accretion and feedback prescriptions both differ from those used in previous numerical simulations of BH growth and feedback. The results in this Letter are taken from a larger set of calculations (DeBuhr et. al., in preparation) and represent general features of all the simulations we have carried out.

2 METHODS

We use a non-public update of the TreeSPH code GADGET-2 (Springel 2005) to perform simulations of galaxy mergers with feedback from both star formation and central supermassive BHs. The code, provided by V. Springel, includes the effective star formation model of Springel & Hernquist (2003). We describe below the additional modifications that we have implemented to model BH growth and feedback.

The multiphase equation of state of Springel & Hernquist (2003) overpredicts the ‘sound speed’ as compared to observations of the random velocities in galaxies (in atomic or molecular gas). For example, the parameter choices $T_{SN} = 4 \times 10^4 \text{K}$, $A_0 = 4000$, $t_0 = 8.4 \text{ Gyr}$ and $q_{EOS} = 0.5$, which have been used in previous works (Springel et al. 2005b), predict $v_s \sim 30 \text{ km s}^{-1}$ at $n \sim 1 \text{ cm}^{-3}$ and $v_s \sim 110 \text{ km s}^{-1}$ for $n \sim 10^3 \text{ cm}^{-3}$. These are too large by a factor of $\sim 2–3$ compared with the observed values (Downes & Solomon 1998). To account for this difference, we reduce the pressure everywhere by a constant factor of 10. As in Springel & Hernquist (2003), we assume that $\rho_s \sim \rho^{1.5}$ for consistency with observations (Kennicutt 1988). The normalization of the star formation prescription is chosen so that a Milky Way-like galaxy has a total star formation rate of about $1 M_\odot \text{yr}^{-1}$; for galaxies with different surface densities, the result is also consistent with Kennicutt (1988). By reducing the pressure at fixed $\rho$ by a factor of 10, the gas is more dense in hydrostatic equilibrium. This would increase the star formation rate relative to the observed value. To correct for this, we modify the equation of state parameters to $t_0^* = 13.86 \text{ Gyr}$, $\beta = 0.1$, $A_0 = 6600$, $T_{SN} = 6.6 \times 10^8 \text{ K}$, $T_{c} = 1000 \text{ K}$ and $q_{EOS} = 0.5$.

The simulations described in this work are all mergers of equal mass galaxies. Each model galaxy consists of a dark matter halo, a rotationally supported disc of gas and stars, a stellar bulge and a central BH. The galaxy parameters are similar to those in Springel et al. (2005b): each galaxy has a total mass of $1.36 \times 10^{12} M_\odot$; the mass of the disc is 4.1 per cent of the total, i.e. $5.57 \times 10^{10} M_\odot$, where 10 per cent of the disc mass is assigned to gas and 90 per cent to stars; the bulge has a mass of $1.86 \times 10^{10} M_\odot$, i.e. one-third of the total disc mass. Each galaxy is made of $8 \times 10^3$ simulation particles and the gravitational force softening is $\epsilon = 47 \text{ pc}$. The halo and the bulge have Hernquist (1990) density profiles, where the virial and half-mass radii of the halo are 229 and 102 kpc, respectively (the concentration is 9.0), and the effective radius of the bulge is 1.27 kpc. The gaseous and stellar discs have exponential profiles with scalelengths $R_d = 3.51 \text{ kpc}$; the scaleheight of the stellar disc is 0.7 kpc, while the scaleheight of the gaseous disc is determined by hydrostatic equilibrium. The massive BH in each galaxy is modelled using a specially marked collisionless tracer particle.

The initial conditions are generated as in Springel et al. (2005b), except for the decrease in gas pressure described above. The galaxies are placed on a prograde parabolic orbit. The individual spins of the two galaxies are randomly chosen to have a relative angle of about 41°. The galaxies begin at a distance of 142 kpc and the orbit has a pericentre of 14.2 kpc.

We estimate the accretion rate on to the BH from the surrounding gas, due to viscous transport of angular momentum, using

$$M_{vis} = 3\pi\alpha \Sigma \frac{c_s^2}{\Omega},$$

where $\Sigma$ is the mean surface density of the gas in the disc, $\Omega$ is its angular rotational frequency and the free parameter $\alpha$ is the dimensionless viscosity; $M_{vis}$ is also capped at the Eddington rate. We compute $\Sigma$ and the sound speed $c_s$ by taking an average of the properties of the individual smoothed particle hydrodynamics (SPH) particles in a spherical region with a radius $R_{acc} = 4c = 188 \text{ pc}$ centred on the BH. Using velocity information directly from the simulation particles themselves to compute $\Omega$ proved to be too noisy; we thus determined $\Omega$ using the total mass, $M_\star$, inside $R_{acc}$ through $\Omega^2 = GM_\star/R_{acc}^3$.

Note that in our accretion prescription, $M_{vis} = 0$ if there is no gas within $4c$ of the BH. This feature of our model accounts for the fact that our simulations capture the angular momentum transport produced by gravitational torques on large scales ($\gtrsim 4c = R_{acc}$); we assume, as is physically reasonable but by no means proven, that these must be sufficient to bring gas close to the BH (within $R_{acc}$) for significant BH accretion to proceed.

Equation (2) is reminiscent of an $\alpha$ prescription of Shakura & Sunyaev (1973), but in this formulation $\alpha$ parametrizes both the efficiency of angular momentum transport on scales smaller than our gravitational force softening (by e.g. gravitational torques) and the uncertainty due to the fraction of the inflowing mass that turns into stars versus accreting on to the central BH. The physical processes responsible for transporting gas from $\sim 1$ kpc to $\sim 0.1$ pc are still not

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fully understood (Goodman 2003), but non-axisymmetric gravitational torques are likely responsible (Shlosman, Frank & Begelman 1989). Detailed calculations of the structure of AGN discs from $\sim 0.01$ to 100 pc, based on transport by spiral waves, show that equation (2), evaluated at radii of $\sim 30$–100 pc, can provide a reasonable estimate of the accretion rate on to the BH in some cases (Thompson, Quataert & Murray 2005). Although equation (2) is only a crude approximation to the true accretion rate on to the BH, it captures the qualitative physics of accretion induced by angular momentum transport and is thus, we believe, a more suitable ‘sub-grid’ model than equation (1). Our fiducial choice for $\alpha$ is $\alpha = 0.05$, but we also present results for 0.15 in Section 3. In the future, we intend to better calibrate our model of angular momentum transport using simulations that focus on the central $\sim 100$ pc of galaxies (Hopkins & Quataert 2009).

To model the feedback on to the gas surrounding the BH, we have implemented a simple phenomenological model in which the AGN’s luminosity $L$ is coupled back into the surrounding gas by depositing momentum radially outwards from the BH. Our goal is to account for the radiation pressure produced by the absorption and scattering of the AGN’s radiation by dust in the ISM. To accurately do so would require a radiation transport calculation, which is beyond the scope of this Letter. Instead, we model the impact of this radiation on the surrounding galaxy by depositing a total momentum (per unit time) of

$$\tau L/c, \quad \text{where} \quad L = \min(\eta M_{\text{vis}} c^2, L_{\text{Edd}}),$$

(3)

radially away from the BH into every SPH particle within a distance of $R_{\text{acc}}$ from the BH; each particle receives the same acceleration. Note that the number of particles that receive this extra force, $N$, will change with time as particles enter and leave the central region of radius $R_{\text{acc}}$. We assume a radiative efficiency of $\eta = 0.1$. Equation (3) models the absorption by the dust of the UV radiation from the AGN (one $L/c$) and, more importantly, the subsequent diffusion of the far-IR (FIR) photons ($\tau L/c$). In this way, the value of $\tau$ determines the total momentum deposited and corresponds to the total FIR optical depth in the nuclear region; we choose $\tau = 10$ in these calculations. This value of $\tau$ is consistent with the fact that even the FIR radiation produced by dust is optically thick at radii of $\sim 100$ pc during galaxy mergers (e.g. Thompson et al. 2005). In particular, $\tau \sim 10$ is motivated by the surface density of $\Sigma \sim 3$ g cm$^{-2}$ in the inner $\sim 100$ pc near the peak of accretion and an FIR opacity of $\sim 3$ cm$^2$ g$^{-1}$. The exact value of $\tau$ does not significantly affect our conclusions, but it does normalize the values of $M_{\text{vis}}$ and $M_{\text{BH}}$ (see equation 4).

The strength of the feedback on an individual particle depends not only on the luminosity, but also on the number of particles, $N$, to which the force is being applied in a given time-step. Our results do not depend strongly on $N$; this is because the momentum is quickly shared with the rest of the gas particles via pressure forces. We carried out a number of test problems on the evolution of gaseous shells with the additional force $\tau L/c$; these explicitly show no dependence on $N$ (DeBuhr et. al., in preparation).

Computing the accretion rate on to and the feedback from the BH in the simulations is prone to noise induced by the stochastic motion of the BH particle. To avoid this ‘Brownian’ motion, we choose a mass for the BH tracer particle of $2.8 \times 10^7$ $M_\odot$, which is roughly a factor of 100 higher than the other particle masses in the simulation. Note that this mass is an artificial dynamical mass for simulation purposes; in addition to this, we integrate $\dot{M}(t)$ to determine the ‘true’ $M_{\text{BH}}$. Once the two BH tracers have a separation of $4R_{\text{acc}}$ or smaller, we consider that they would coalesce to form a single BH.

Once the tracers merge, the two values of $M_{\text{BH}}$ are summed and one of the BH particles is moved to the centre of mass of the two tracers and the other is removed from the region.

### 3 RESULTS

The top panel of Fig. 1 shows the viscous accretion rate on to the BH for the fiducial run with $\alpha = 0.05$ (black) and for a run with $\alpha = 0.15$ (blue). For comparison, the Eddington rate $M_{\text{Edd}} \equiv L_{\text{Edd}}/c^2 \eta$ is shown in grey, using the BH mass as a function of time from our fiducial simulation. The accretion rate is relatively constant at early times but then peaks during the first close passage of the two galaxies at $\sim 0.75$ Gyr and then even more strongly as the two galaxies complete their merger at $\sim 1.6$ Gyr; note that $M \ll M_{\text{Edd}}$ at both early and late times but reaches $\sim M_{\text{Edd}}$ for $\sim 100$ Myr near both first and final passage.

One of the interesting results in Fig. 1 is that differences in $\alpha$ do not significantly change the accretion rate on to the BH, particularly near the peaks of activity. This is contrary to what one might expect from the fact that $M_{\text{vis}} \propto \alpha$ (equation 2). The origin of the weak dependence of $M_{\text{vis}}$ on $\alpha$ is that when the supply of mass is large, feedback from accretion on to the BH regulates the rate at which the BH accretes. Previous work has shown that there is a critical luminosity $L_{\text{c}}$ at which the outward radiation pressure force due to the central AGN just balances the inward force of gravity. For

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Top panel: viscous accretion rate $M_{\text{vis}}$ on to the BH (equation 2) for our fiducial galaxy merger simulation ($\alpha = 0.05$; black) and for a run with three times the viscosity ($\alpha = 0.15$; blue). Also shown is the critical mass accretion rate $M_{\text{c}}$ (equation 4) at which radiation pressure can push gas out of the nuclear region (red), and the Eddington rate $M_{\text{Edd}}$ (grey). Note that the accretion rate adjusts to $M_{\text{vis}} \sim M_{\text{c}}$ during the peaks of activity, independent of $\alpha$. Bottom panel: viscous accretion rate for the fiducial simulation (black) as compared to a simulation without feedback (orange; $\alpha = 0.15$); also shown is the Bondi accretion rate using the BH mass from the fiducial simulation. Unlike $M_{\text{vis}}$, the Bondi rate is $\approx M_{\text{Edd}}$ at nearly all times.
a simple spherically symmetric problem, this is given by \( \tau L/c = 4 f_\sigma^2/G \), where \( f_\sigma \) is the gas fraction in the nuclear region and \( \sigma^2 = GM/2R_{\text{acc}} \), with \( M \) being the total mass within \( R_{\text{acc}} \) (Murray et al. 2005). This in turn implies a critical accretion rate \( M_\ast \):

\[
M_\ast = \frac{4 f_\sigma}{\tau_{\text{vis}} c^4} \sigma^4. \tag{4}
\]

For \( L \gtrsim L_c \), the radiation force on gas in the nuclear region exceeds the inward force of gravity, and thus gas in the vicinity of the BH will be pushed out of the nuclear region. In our model, the accretion rate is determined by the gas properties within \( R_{\text{acc}} \approx 188 \) pc; thus if the gas is largely pushed out of the nuclear region, the accretion rate on to the BH decreases. When \( L \lesssim L_c \), gravitational torques can drive gas into the nuclear region towards the BH, thus increasing \( M_{\text{vis}} \). This suggests that the accretion rate may self-adjust such that \( M_{\text{vis}} \sim M_\ast \). To quantify this, the top panel of Fig. 1 shows \( M_\ast \) computed within \( 2R_{\text{acc}} \) of the BH for the fiducial calculation (red). The accretion rate is indeed \( \sim M_\ast \) near the peaks of activity. This highlights that although \( M_{\text{vis}} \ll M_\ast \) is certainly possible if there is insufficient gas in the nuclear regions (e.g. after the merger), feedback limits the maximum rate at which the BH can accrete to be \( \sim M_\ast \). One point that we return to below is that although feedback does have a strong effect on the gas dynamics in the galactic nuclei, it is not strong enough to blow large amounts of gas out of the galaxy as a whole.

The bottom panel of Fig. 1 compares the accretion rate for the fiducial run (black) and a similar run with no BH feedback (orange; \( \alpha = 0.15 \)). The peak accretion rate is a factor of \( \sim 10 \) higher in the case without feedback, and the duration of activity is significantly longer; moreover, \( M_{\text{vis}} \) in the absence of feedback is \( \propto \alpha \) and so can be scaled up or down by arbitrary amounts by varying \( \alpha \), unlike in the presence of feedback (top panel). Also shown in the lower panel is the Bondi accretion rate (grey) with the BH mass set by that in the fiducial run (which uses \( M_{\text{vis}} \)). For nearly all of the simulation, \( M_{\text{Bondi}} \approx M_{\text{Bondi}} \), and unlike the simulations of Springel et al. (2005b) or Johansson et al. (2009), the Bondi rate does not decrease after the final merger, because the ambient gas remains cool and dense.

Fig. 2 shows the column density of gas in the vicinity of the BH for the case without feedback (right) and for the case with feedback (left), both at the same time during the peak of accretion at \( t = 1.74 \) Gyr. The images are 28.5 kpc on a side in the top row and 4.28 kpc on a side in the bot- tom row. In the simulation with feedback, one can see explicitly that the gas has been evacuated from the region near the BH (within \( \sim R_{\text{acc}} \)), as argued above. These images also demonstrate that the feedback from the BH does not produce a large-scale blow-out of matter from the galactic nucleus. More quantitatively, at the end of the simulation, the runs with and without feedback have the same mass of gas outside \( 4R_d \) to within 10 per cent, and the mass that is at large radii is due to the merger dynamics (e.g. tidal tails) rather than the BH driving a powerful outflow. This is qualitatively consistent with observational evidence for large reservoirs of atomic and molecular gas in nearby luminous AGN and quasars (Scoville et al. 2003), which have relatively normal kinematics (Ho et al. 2008). By contrast, previous simulations using the Bondi accretion rate and thermal feedback find that the BH unbinds the remaining gas in the galaxy near the end of the merger (e.g. Di Matteo et al. 2005) and that this can be important for shutting off star formation in ellipticals (Springel et al. 2005a).

In Fig. 3 we show the BH mass \( M_{\text{BH}} \) and the integrated mass of stars formed during the merger (\( M_* \)) for the fiducial simulation (black), the run without feedback (orange, dash-dotted), and the run with feedback (red). One point that we return to below is that although feedback does have a strong effect on the gas dynamics in the galactic nuclei, it is not strong enough to blow large amounts of gas out of the galaxy as a whole.

\[ M_{\text{vis}} \sim M_\ast \]
self-regulated accretion during most stages of the merger. There is, of course, freedom in choosing the initial mass of the BH in our calculations, but so long as this is sufficiently small, it does not significantly change the final mass of the BH. For the simulations without feedback, the final BH mass is larger than in the presence of feedback by a factor of $\approx 10$, as would be expected from Fig. 1. In addition, the mass of the BH scales $\propto \alpha$ in this case. Although we have not made a quantitative comparison, the small dispersion in BH mass for different subgrid accretion models in the presence of feedback appears consistent with the small scatter in the $M_{\text{BH}}-\sigma$ relation (while models without feedback would produce a larger dispersion in $M_{\text{BH}}$).

4 DISCUSSION

The model presented here is a necessarily simplified treatment of the physics occurring in the nuclear regions of galaxies. In particular, the choices of $\alpha$ in the accretion model and of $R_{\text{acc}}$ and $\tau$ in the model of momentum deposition are somewhat uncertain. Changing these values affects some of the details of the gas dynamics. For instance, the accretion history of the BH changes modestly as we vary $R_{\text{acc}}$ and $\tau$. However, it is encouraging that many of the global results of the simulations are insensitive to these choices. The peak luminosity occurs at the same time and always reaches the Eddington limit. The total stellar mass formed during a merger is essentially independent of these parameters and the final BH mass is relatively insensitive to both $R_{\text{acc}}$ and $\alpha$. Perhaps most interestingly, the peak accretion rate is relatively independent of the subgrid accretion model ($\alpha$) and is instead set by the structure of the host galaxy and the feedback physics, reaching the critical rate $\sim \dot{M}_e$ at which radiation pressure balances gravity in the nuclear regions of the galaxy (equation 4).

A clear next step in this modelling effort is to perform radiative transfer calculations simultaneously with the SPH calculation in order to more reliably determine the radiation pressure force. This would not only eliminate the need to specify the parameters $R_{\text{acc}}$ and $\tau$ by hand, but would also provide information about the AGN spectrum as a function of time. Detailed comparisons between these results and observations should allow quantitative tests of the importance of AGN feedback by momentum deposition during BH growth and galaxy formation.

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