The accretion disc particle method for simulations of black hole feeding and feedback

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ABSTRACT
Black holes grow by accreting matter from their surroundings. However, angular momentum provides an efficient natural barrier to accretion and so only the lowest angular momentum material will be available to feed the black holes. The standard subgrid model for black hole accretion in galaxy formation simulations – based on the Bondi–Hoyle method – does not account for the angular momentum of accreting material, and so it is not clear how representative the black hole accretion rate estimated in this way is likely to be. In this paper we introduce a new subgrid model for black hole accretion that naturally accounts for the angular momentum of accreting material. Both the black hole and its accretion disc are modelled as a composite accretion disc particle. Gas particles are captured by the accretion disc particle if and only if their orbits bring them within its accretion radius \( R_{\text{acc}} \). Gas particles are captured by the accretion disc particle if and only if their orbits bring them within its accretion radius \( R_{\text{acc}} \), at which point their mass is added to the accretion disc and feeds the black hole on a viscous time-scale \( t_{\text{visc}} \). The resulting black hole accretion rate \( M_{\text{BH}} \) powers the accretion luminosity \( L_{\text{acc}} \propto M_{\text{BH}}^2 \), which drives black hole feedback. Using a series of controlled numerical experiments, we demonstrate that our new accretion disc particle method is more physically self-consistent than the Bondi–Hoyle method. We also discuss the physical implications of the accretion disc particle method for systems with a high degree of rotational support, and we argue that the \( M_{\text{BH}}^\sigma \) relation in these systems should be offset from the relation for classical bulges and ellipticals, as appears to be observed.

Key words: accretion, accretion discs – methods: numerical – galaxies: active – galaxies: formation.

1 INTRODUCTION
Understanding how super-massive black holes at the centres of galaxies grow over cosmic time is one of the most important yet challenging problems facing modellers of galaxy formation. Observationally there is clear and compelling evidence that in galaxies that host super-massive black holes the black hole mass \( M_{\text{BH}} \) correlates strongly with the stellar mass \( M_\star \) and velocity dispersion \( \sigma \) of the host bulge (e.g. Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002; Haring & Rix 2004; Gültekin et al. 2009). Theoretically these correlations are widely interpreted as hallmarks of black hole feedback, which itself is a natural consequence of accretion on to the black hole (e.g. Silk & Rees 1998; Fabian 1999; King 2003, 2005; Sazonov et al. 2005). In this picture, feedback acts to regulate the black hole’s mass accretion rate \( \dot{M}_{\text{BH}} \) by modifying the physical and dynamical state of gas in and around its host galaxy – so the greater \( M_{\text{BH}} \), the stronger the feedback and the greater the impact on \( M_{\text{BH}} \). Therefore, how one estimates \( M_{\text{BH}} \) is crucial because it governs not only the rate at which the black hole grows but also the strength of the black hole feedback. This is a particularly important problem because how black hole feeding and feedback is modelled can have a profound impact on the predictions of how galaxies form (e.g. Bower et al. 2006; Croton et al. 2006).

The standard approach to estimating \( M_{\text{BH}} \) in galaxy formation simulations is based on the work of Bondi & Hoyle (1944) and Bondi (1952) (hereafter the Bondi–Hoyle method; cf. Di Matteo, Springel & Hernquist 2005; Springel, Di Matteo & Hernquist 2005). In the accretion problem as it was originally formulated, a spherically symmetric accretion flow is captured gravitationally by a point-like accretor from a uniform distribution of gas with zero angular momentum. Under these conditions, the accretion rate on to the accretor \( \dot{M}_{\text{Bondi}} \) is proportional to the square of the black hole mass \( M_{\text{BH}}^2 \) and the gas density \( \rho \), and inversely proportional to the cube of the sound speed \( c_s \). This gives an accretion rate \( \dot{M}_{\text{Bondi}} \propto M_{\text{BH}}^2 \rho / c_s^3 \). The assumption in galaxy formation simulations is that \( M_{\text{BH}} \propto \dot{M}_{\text{Bondi}} \) (see, e.g. the discussion in Booth & Schaye 2009).

However, there are good physical reasons to believe that \( \dot{M}_{\text{Bondi}} \) cannot be representative of the true black hole accretion rate \( M_{\text{BH}} \) in an astrophysically realistic situation (cf. King 2010). First, the black hole is embedded in the gravitational potential of a galaxy that is orders of magnitude more massive than it; this means that...
the gravitational force acting on the accretion flow is dominated by the mass of the galaxy rather than the black hole and so $M_{\text{Bondi}}$ will be a similar number of orders of magnitude off the true $M_{\text{BH}}$ (we show this explicitly in Hobbs et al., in preparation). Secondly, any astrophysically realistic accretion flow will have some angular momentum, violating one of the key assumptions made in calculating $M_{\text{Bondi}}$. This is important because it implies that infalling material will settle on to a circular orbit whose radius $R_{\text{acc}}$ is set by the angular momentum of the material with respect to the black hole (cf. Hobbs et al. 2010). In particular, it means that only the very lowest angular material will be available to feed the black hole because the time-scale required for viscous transport of material through the disc is of order a Hubble time on scales of order $R \sim 1-10$ pc (see, e.g. King 2010). This is a very restrictive condition because it is not straightforward for infalling gas to lose its angular momentum other than by colliding with other gas, which leads to angular momentum cancellation. Therefore, angular momentum provides an efficient natural barrier to accretion by the black hole, and so must be accounted for when estimating $M_{\text{BH}}$.

These arguments make clear that the Bondi–Hoyle method cannot provide a reliable estimate of $M_{\text{BH}}$ in galaxy formation simulations. If feedback from black holes plays an important role in galaxy formation as we expect it to (e.g. Bower et al. 2006; Croton et al. 2006), then it is crucial that we devise an alternative method for estimating $M_{\text{BH}}$ in galaxy formation simulations that overcomes the problems that beset the Bondi–Hoyle method.

In this short paper, we introduce our new ‘accretion disc particle’ method (hereafter the ADP method) for estimating $M_{\text{BH}}$ in galaxy formation simulations, which accounts naturally for the angular momentum of infalling material. We use a collisionless ADP to model the black hole and its accretion disc. The black hole accretes if and only if gas comes within the accretion radius $R_{\text{acc}}$ of the ADP, at which point it is captured and added to the accretion disc that feeds the black hole on a viscous time-scale $t_{\text{visc}}$. In this way the black hole will accrete only the lowest angular momentum material from its surroundings.

The layout of this paper is as follows. We describe the main features of the ADP method in Section 2, showing how the accretion rate $M_{\text{acc}}$ on to the ADP is linked to the black hole accretion rate $M_{\text{BH}}$. In Section 2.2 we discuss briefly our momentum-driven feedback model (cf. Nayakshin & Power 2010) as well as our implementation of the quasar pre-heating model of Sazonov et al. (2005). The accretion rate $M_{\text{BH}}$ estimated using the ADP method is very different from one estimated using the Bondi–Hoyle method. We show this clearly in Section 3 using simple idealized numerical simulations, designed to illustrate the key differences between the ADP and Bondi–Hoyle methods for estimating $M_{\text{BH}}$. These simulations follow the collapse of an initially rotating shell of gas on to a black hole embedded in an isothermal galactic potential. Finally we summarize our results in Section 4 and we discuss the implications for galaxy formation simulations and the $M_{\text{BH}} - \sigma$ relation in Section 5.

## 2 Modelling Accretion and Feedback

### 2.1 The accretion model

#### 2.1.1 The ADP Method

The main features of the ADP are illustrated in Fig. 1. The ADP is collisionless and consists of a sink particle (Bate, Bonnell & Price 1995) with an accretion radius $R_{\text{acc}}$. $R_{\text{acc}}$ is a free parameter of the simulation but in general it is desirable to set it to the smallest resolvable scale in the simulation, which will be of the order of the gravitational softening length of the gas particles. The total mass of the sink particle is equal to the sum of the masses of the black hole, $M_{\text{BH}}$, and its accretion disc, $M_{\text{disc}}$. The accretion disc is assumed to be tightly bound to the black hole and is thus a property of the sink particle rather than a separate entity.

Accretion on to the black hole in the ADP method is a two-stage process. First, any gas that crosses the accretion radius $R_{\text{acc}}$ is removed from the computational domain and added to the accretion disc. In the classical sink-particle method of Bate et al. (1995), the accreted gas would be added to the black hole immediately, but in an astrophysically realistic situation, the finite non-zero angular momentum of the accreted gas leads to the formation of an accretion disc before the gas can accrete on to the black hole. Here we assume that gas is added to the accretion disc after a time that is of order the dynamical time-scale $t_{\text{dyn}}$ at $R_{\text{acc}}$.

Secondly, gas is transported through the accretion disc and is added to the black hole. In principle, we could describe the evolution of the accretion disc by the standard viscous disc evolution equations (see, e.g. chapter 5 of Frank, King & Raine 2002). However, neither theory nor observation tells us what the magnitude of the disc viscosity should be and so we cannot be sure of the efficiency of angular momentum transport within the disc. Moreover, if the accretion disc is sufficiently massive to become self-gravitating, then a significant fraction of its gas mass can be converted to stars (see, e.g. Toomre 1964; Paczyński 1978; Shlosman & Begelman 1989; Goodman 2003; Nayakshin, Cuadra & Springel 2007). Star formation depletes the gas reservoir, reducing $M_{\text{BH}}$, but stellar feedback can act to either reduce or enhance $M_{\text{BH}}$ (e.g. Cuadra, Nayakshin & Martins 2008; Schartmann et al. 2009). Solving the standard viscous disc evolution equations is no longer straightforward under these circumstances and detailed accretion disc simulations are required (see, e.g. Cuadra et al. 2008).

We want a simple subgrid model, however, and so we simplify the problem. To this end, we assume that (a) an accretion disc forms and (b) angular momentum transport through the disc introduces a delay between the time a gas particle crosses $R_{\text{acc}}$ and the time that it is accreted by the black hole. This time delay will be of the order of the disc viscous time, $t_{\text{visc}}$, which can be of order the Hubble
time for accretion discs around super-massive black holes (cf. King 2010). To capture this in the simplest way we describe the evolution of the accretion disc by

\[ \dot{M}_{\text{disc}} = \dot{M}_{\text{acc}} - \dot{M}_{\text{BH}}, \]

where \( \dot{M}_{\text{acc}} \) is the rate at which gas is captured through \( R_{\text{acc}} \) and \( \dot{M}_{\text{BH}} \) is the accretion rate on to the black hole. \( t_{\text{visc}} \) can be estimated using physical arguments (see, e.g. section 2 of King 2010) but, as argued above, it is uncertain, and so we treat \( t_{\text{visc}} \) as a free parameter instead. In general we require that \( t_{\text{visc}} \gtrsim t_{\text{dyn}}(R_{\text{acc}}) \) and typically set \( t_{\text{visc}} \sim 10–100 \) Myr in galaxy formation simulations (Power et al., in preparation).

Note that the rate at which gas is captured from the ambient medium is not limited in any way: it is simply governed by the evolution of the large scale accretion flow into the centre of the galaxy. In contrast, the rate at which gas is accreted on to the black hole is limited by the Eddington accretion rate \( \dot{M}_{\text{Edd}} \),

\[ \dot{M}_{\text{Edd}} = \frac{4\pi G M_{\text{BH}} m_p}{\eta \sigma_T c}, \]

where \( m_p \) is the proton mass, \( \sigma_T \) is the Thomson cross-section, \( c \) is the speed of light and \( \eta \) is the accretion efficiency, for which we assume the standard value of \( \eta = 0.1 \). This means that \( \dot{M}_{\text{BH}} \) in equation (1) satisfies

\[ \dot{M}_{\text{BH}} = \min \left[ \dot{M}_{\text{disc}}, \dot{M}_{\text{Edd}} \right]. \]

This simple system of equations can be expanded in the future to encompass more detailed disc modelling, including gas disc self-gravity and the resulting star formation and feedback from stars formed there. Given the empirical evidence from our Galactic Centre (e.g. Nayakshin & Cuadra 2005; Paumard et al. 2006) and the theoretical expectation that nuclear stellar cluster feedback should be important (cf. Nayakshin, Wilkinson & King 2009b), this is likely to be an important step in future studies.

It is worth making some additional comments about our ADP method and how it relates to the classical sink particle formulation of Bate et al. (1995). In the classical sink particle formulation, a number of conditions had to be satisfied before gas could be accreted by the sink particle (e.g. pressure forces at the accretion radius, comparison of thermal and gravitational binding energy with respect to the sink particle, etc.). In our approach, there is a single condition for accretion, namely that gas comes within \( R_{\text{acc}} \). Physically this is quite reasonable. The virial temperature in the vicinity of a super-massive black hole is very high, typically in the range of \( 10^6–10^8 \) K. However, gas densities are also very high near \( R_{\text{acc}} \) and so cooling times are expected to be very short (e.g. King 2005). This implies that gas is likely to be much cooler than the virial temperature, which means that both the pressure forces and thermal energy of the gas is negligible. Furthermore, viscous times are always very long compared with dynamical times, so we expect the accretion disc to be a long-lived (essentially permanent) feature within \( R_{\text{acc}} \). This means that gas that comes within \( R_{\text{acc}} \) is very likely to undergo a large Mach number collision with the disc, causing it to shock and then cool rapidly. Therefore, even if gas is initially on an unbound (hyperbolic) orbit around the sink particle, it will most likely lose most of its bulk and thermal energy and settle into the accretion disc.

2.1.2 The Bondi–Hoyle Method

The Bondi–Hoyle method for estimating \( \dot{M}_{\text{BH}} \) is the standard approach in galaxy formation simulations (see, e.g., Di Matteo et al. 2005; Springel 2005; Booth & Schaye 2009). Here the black hole accretion rate is calculated directly from

\[ \dot{M}_{\text{BH}} = \frac{4\pi \alpha G^2 M_{\text{BH}} \rho}{(c_s^2 + v^2)^{3/2}}, \]

where \( \rho \) is the smoothed particle hydrodynamics (SPH) density at the position of the black hole, \( c_s \) is the sound speed of the gas, \( v \) is the velocity of the black hole relative to the gas and \( \alpha \) is a fudge factor that we set to unity for the purposes of this work, but which can be of the order of \( 100–300 \) (see the discussion in Booth & Schaye 2009). In practice we compute estimates for \( \rho, c_s \) and \( v \) using the SPH smoothing kernel with \( N_{\text{sp}} = 40 \) neighbours. Note that there is no explicit dependence on the angular momentum of the gas in equation (4) – the accretion rate is dictated by the gas density \( \rho \) and sound speed \( c_s \).

2.2 The feedback model

In the simulations presented in the next section, we use \( \dot{M}_{\text{BH}} \) estimated using either equation (3) or (4) to determine the accretion luminosity of the black hole,

\[ L_{\text{acc}} = \eta \dot{M}_{\text{BH}} c^2; \]

this is Eddington limited, as explained in the previous section. We assume that this radiated luminosity drives a wind that carries a momentum flux \( L_{\text{wind}}/c \), which is usually true for AGN (cf. King & Pounds 2003; King 2010). Wind particles are emitted isotropically by the black hole at a rate

\[ \dot{N}_{\text{wind}} = \frac{L_{\text{acc}}}{c \rho_{\text{wind}}}, \]

and they carry a momentum \( p_{\text{wind}} = 0.1 m_{\text{gas}} \sigma, \) where \( \sigma \) is the velocity dispersion of the host halo. This satisfies the requirement \( p_{\text{wind}} \ll p_{\text{gas}}, \) where \( p_{\text{gas}} \) is the typical gas particle momentum (\( \sim m_{\text{gas}} \sigma \) here), and ensures that Poisson noise from our Monte Carlo scheme does not compromise our results (see Nayakshin, Cha & Hobbs 2009a).

In addition to this momentum-driven wind, we include the quasar pre-heating model of Sazonov et al. (2005). In this model, the average quasar spectral energy distribution derived by Sazonov, Ostriker & Sunyaev (2004) is used to estimate an equilibrium temperature \( T_{\text{eq}} \) for the gas based on the ionization parameter \( \xi = (n e)/n(r^2) \), where \( n(r) \) is the number density of radius \( r \). Physically \( T_{\text{eq}} \) corresponds to the temperature at which heating through Compton scattering and photoionization balances Compton cooling and cooling as a result of continuum and line emission, on the assumption that gas is in ionization equilibrium. In practice, we calculate heating and cooling rates using formulae A32 to A39 in appendix 3.3 of Sazonov et al. (2005), and we find that the resulting equilibrium temperature profile of the gas is well approximated by their equation (3),

\[ T_{\text{eq}}(\xi) \approx 200\xi \text{K}. \]

This holds over the temperature range \( 2 \times 10^4–10^7 \) K; for \( \xi \ll 100 \) and \( \xi \gg 5 \times 10^4, T_{\text{eq}} \approx 10^4 \) and \( 2 \times 10^7 \) K, respectively.

3 RESULTS

We have run simple idealized numerical simulations that are designed to show that our ADP method constitutes a physically self-consistent subgrid model for estimating the black hole accretion rate \( \dot{M}_{\text{BH}} \) in galaxy formation simulations, and that the Bondi–Hoyle method does not.
Our initial condition is a spherical shell of gas of a uniform density $\rho_0$, distributed between the inner and outer radii, $R_{\text{in}}$ and $R_{\text{out}}$, respectively. The shell is embedded in the static analytic gravitational potential of a singular isothermal sphere with a 1D velocity dispersion $\sigma$ and modified slightly to have a constant density core within $R \leq R_{\text{core}}$. For all the runs in this paper, we adopt $\rho_0 \simeq 10^{10} M_\odot$ kpc$^{-3}$, $R_{\text{in}} = 0.067$ kpc, $R_{\text{out}} = 0.1$ kpc, $R_{\text{core}} = 0.01$ kpc and $\sigma = 147$ km s$^{-1}$. The shell has a mass of $M_{\text{shell}} = 3 \times 10^7 M_\odot$ and is realized with $\sim$280,000 gas particles, drawn from a uniform density glass, which means that the particle mass is $m_p \simeq 1.1 \times 10^7 M_\odot$. We give the shell an initial temperature of $10^4$ K and an initial bulk rotation around the $z$ axis such that its rotational velocity in the $xy$ plane is $v_{\phi} = v_{\text{rot}} = f_{\text{rot}} \sqrt{2\sigma}$ with $f_{\text{rot}} = 0.3$; it falls from rest in the radial direction. Finally we embed a collisionless particle – corresponding to the black hole – at rest at the centre of the potential; the initial black hole mass is $M_{\text{BH}} = 10^6 M_\odot$ and, in the cases where we use the ADP model, an initially zero disc mass.

All of the simulations are run using GADGET3, an updated version of the code presented in Springel (2005). Each simulation is run for $\sim$4.7 Myr, which corresponds to $\sim$14 dynamical times at the initial outer radius of the shell.

3.1 Without feedback

We begin by considering the simplest possible case – the collapse of the shell in the absence of any feedback from the black hole. We model the black hole using an ADP, but in this particular simulation we decouple the accretion luminosity $L_{\text{acc}}$ of the black hole from $M_{\text{BH}}$ by setting $\eta = 0$ in equation (5); this suppresses both the momentum-driven wind and quasar pre-heating. We choose an accretion radius of $R_{\text{acc}} = 0.003$ kpc. For simplicity, we assume an isothermal equation of state with a temperature of $T = 10^4$ K.

By conservation of angular momentum, the shell should settle into a thin rotationally supported disc (cf. Hobbs et al. 2010). This disc is distinct from, and on a much larger scale than, the accretion disc discussed in Section 2.1, which is tightly bound to the black hole on a scale much smaller than we can resolve in our simulation. We show the gas density projected on to the $xy$ and $xz$ planes at $t = 4.7$ Myr (upper and lower panels, respectively) in Fig. 2. The gas is distributed in a thin rotating disc; its inner and outer boundaries are at $\sim$0.006 and $\sim$0.01 kpc, respectively, and it rotates in a clockwise sense around the $z$ axis (indicated by the projected velocity vectors). The inner boundary is larger than the accretion radius $R_{\text{acc}} = 0.003$ kpc by a factor of $\sim$2 and so only a small fraction of the mass of the disc comes within $R_{\text{acc}}$ over the duration of the simulation ($\sim$20 particles or $\sim$0.007 per cent after $\sim$4 Myr).

The absence of any accretion until late times might seem counterintuitive, given that our initial condition is a rotating shell of gas. What happens to material with small angular momentum that lies along the axis of rotation? Why does it not accrete rapidly on to the black hole? Hobbs et al. (2010) have shown that this small angular momentum gas shocks and mixes with larger angular momentum gas, which increases its net angular momentum and provides a barrier to accretion.

Note that there are knots of high density material in the disc. For expediency, we tag gas particles that exceed a threshold value

\footnote{This is larger than the gravitational softening of gas particles by a factor of $\sim$20, but slightly smaller than the inner edge of large-scale gas disc we expect to form. We choose a large value to highlight that our initial conditions lead to minimal accretion on to the black hole, by construction.} in local density. Physically these high density regions are likely to host star formation, but for the purpose of this study we simply decouple these particles hydrodynamically from other gas particles, ignoring them in the hydrodynamical force calculation, which helps to increase the speed of the simulation. In this particular run, $\sim$90 per cent of the gas particles are converted to decoupled particles by $t \simeq 4.7$ Myr.

3.2 With feedback

Let us now consider the evolution of the collapsing shell when the black hole accretion luminosity $L_{\text{acc}}$ is coupled to $M_{\text{BH}}$, as in equation (5). We estimate $M_{\text{BH}}$ using the ADP method (equations 1 and 3 with $R_{\text{acc}} = 0.003$ kpc and $t_{\text{visc}} \simeq 10^4$ yr) and the Bondi–Hoyle method (equation 4 with $\alpha = 1$). Note that, for the purpose of this study, the precise value of $t_{\text{visc}}$ is unimportant; the point is that in
the cases that we consider, the ADP method predicts a negligible accretion rate, as we would expect from physical arguments. In both cases we assume that the black hole feedback takes the form of a momentum-driven wind and quasar pre-heating. The gas is initially isothermal with a temperature of \( T = 10^4 \) K, but as it evolves it can heat and cool in response to, e.g., the quasar radiation field.

In Figs 3 and 4 we show the gas density projected on to the \( xy \) and \( xz \) planes (upper and lower panels, respectively) in the ADP and Bondi–Hoyle runs (left- and right-hand panels) at \( t = 1 \) and 4.7 Myr. As in Fig. 2, arrows indicate the magnitude and direction of the projected velocity vectors of the gas. The differences between the runs are striking. The shell should settle into a thin rotationally supported disc whose properties are very similar to those of the disc shown in Fig. 2 and indeed this is the case in the ADP run. This is unsurprising – because we link feedback explicitly to accretion rate on to the black hole, we do not expect any significant feedback in the ADP run because the angular momentum of the gas is too large to bring it within \( R_{\text{acc}} \) until late times. Even at this point, the mass of gas accreted \( M_{\text{acc}} \ll 1 \) per cent of the initial shell mass over the lifetime of the simulation and \( \dot{M}_{\text{BH}} \ll M_{\text{Edd}} \), which means that the feedback is weak and has little effect on the gas distribution. We
Figure 4. Late times: the gas density projected on to the $xy$ and $xz$ planes (upper and lower panels) in the ADP and Bondi–Hoyle runs (left- and right-hand panels) at $t \approx 4.7$ Myr.

Note also that, as in the run without feedback, $\sim 92$ per cent of the gas particles have decoupled into high density knots by $t \approx 4.7$ Myr.

In contrast, the accretion rate is consistently Eddington limited over the duration of the simulation in the Bondi–Hoyle run. The black hole is not massive enough for its feedback to prevent the collapse of the shell into a disc (cf. right-hand panels of Fig. 3), but once the disc has formed, the feedback acts efficiently on the low column density gas. At early times it is the lower column density gas surrounding the disc and along the axis of rotation that is most efficiently driven outwards, principally by the momentum-driven wind. In particular, it is the impact of the feedback along the axis of rotation that imprints the strongly bipolar character on the outflow, evident in the $xz$ projection in Fig. 3. Over time, as high density knots form in the disc, lower density material within the disc is blown away. For example, after $t \approx 1/2.8/4.7$ Myr, $\sim 2$ per cent/25 per cent/40 per cent of the gas particles that have not been decoupled have been expelled from the disc, compared to $\ll 1$ per cent of gas particles in the ADP run. At late times, even the high density knots are ablated. As a result, the cumulative effect of the feedback over $\sim 4.7$ Myr has a profound impact on the gas
distribution, a point that is nicely illustrated in Fig. 5, which makes clear that the gas is distributed over kpc scales (and indeed to \( \sim 10 \) kpc) by the end of the run.

It is worth noting that the fraction of gas that had a sufficiently high density to be decoupled over the lifetime of the Bondi–Hoyle run is comparable to the fraction in the ADP run (88 per cent compared to 90 per cent). However, these high density knots are ablated by the feedback in the Bondi–Hoyle run whereas they survive in the ADP run.

4 SUMMARY

Black holes grow by accreting gas and stars from their surroundings. However, only the lowest angular momentum material can come sufficiently close to the black hole to be accreted, and so any estimate of a black hole’s accretion rate \( \dot{M}_{\text{BH}} \) must account for this. However, the standard subgrid model for black hole accretion in galaxy formation simulations neglects the angular momentum of accreting material (cf. Di Matteo et al. 2005; Springel et al. 2005). The Bondi–Hoyle method (Bondi & Hoyle 1944; Bondi 1952) assumes that \( \dot{M}_{\text{BH}} \propto \rho / c_s^3 \) where \( \rho \) is the gas density at the position of the black hole and \( c_s \) is the sound speed in the gas. This implies that black holes are always accreting; \( \dot{M}_{\text{BH}} \) may be small but it can never be zero, regardless of the angular momentum of the gas surrounding the black hole.

In this short paper, we presented a new subgrid model for estimating \( \dot{M}_{\text{BH}} \) in galaxy formation simulations that accounts for the angular momentum of accreting material. This ADP model uses a collisionless sink particle to model the composite black hole and accretion disc system. The black hole accretes if and only if gas comes within the accretion radius \( R_{\text{acc}} \) of the ADP, at which point its mass is added to the accretion disc that feeds the black hole on a viscous time-scale \( t_{\text{visc}} \). In this way the black hole will accrete only the lowest angular momentum material available to it in and around its host galaxy.

We demonstrated that the ADP method constitutes a physically self-consistent model using simple idealized numerical simulations that follow the collapse of a rotating shell of gas on to a black hole embedded at the centre of an isothermal galactic potential. By construction, the gas settles into a thin rotationally supported disc between \( R_{\text{in}} \) and \( R_{\text{out}} \), where \( R_{\text{min}} > R_{\text{acc}} \), and so we do not expect any accretion on to the black hole. Because we link feedback to accretion, we do not expect there to be any significant differences between simulations with or without feedback when using the ADP estimate of \( \dot{M}_{\text{BH}} \). On the other hand, we expect the evolution of the system to differ if \( \dot{M}_{\text{BH}} \) is estimated using the Bondi–Hoyle method.

These expectations were borne out by the results of our simulations. The Bondi–Hoyle method predicted that \( \dot{M}_{\text{BH}} \) should be Eddington limited over the lifetime of the simulation. Because the feedback in this case was relatively weak, its effect could not prevent the collapse of the shell into a disc, but the cumulative effect of the feedback was to drive gas away and to expel it to \( \sim 10 \) kpc scales after \( \sim 5 \) Myr. In contrast the ADP method predicted negligible accretion rates at all times; the shell collapsed, settled into a thin rotationally supported disc and \( \sim 90 \) per cent of the mass decouples into long-lived high density knots, which correspond to regions of star formation.

5 CONCLUSIONS

We have argued that our new ADP method provides a far more physically motivated and self-consistent approach to modelling black hole accretion than the Bondi–Hoyle method, which is the standard approach in galaxy formation simulations (cf. Di Matteo et al. 2005; Springel et al. 2005). The Bondi–Hoyle method was formulated with a specific astrophysical problem in mind, quite unlike the situations that arise when modelling galaxy formation. It is not applicable to problems in which the accretion flow has non-zero angular momentum (as demonstrated in this paper) and/or in which it is embedded in the potential of a more massive host (as we show in Hobbs et al., in preparation). Therefore it is unsurprising that the Bondi–Hoyle method struggles to capture the behaviour of gas
accretion in these kinds of common situations. Our ADP method is similar in spirit to the ‘accretion radius’ or ‘sink particle’ approaches to modelling accretion that are used extensively in simulating star formation (e.g. Bate et al. 1995; Bate & Bonnell 2005) and modelling gas accretion onto the super-massive black hole at the centre of the Milky Way (Cuadra et al. 2006), and we believe that it is natural to extend this approach into modelling galaxy formation. An important next step in our work, which builds on this ADP method and our recent momentum-driven wind model for feedback (cf. Nayakshin & Power 2010), is to combine the models in simulations of merging galaxies and ultimately cosmological galaxy formation simulations.

It is interesting to consider one important astrophysical consequence of our ADP model and to contrast it with what one would expect using the Bondi–Hoyle model. Recently it has been suggested that there is observationally evidence for separate MBH–σ relations for elliptical galaxies and classical bulges on the one hand and pseudo-bulges on the other, such that the black holes in pseudo-bulges are underweight (see, e.g. Greene, Ho & Barth 2008; Hu 2009). The properties of pseudo-bulges appear to deviate systematically from those of classical bulges, and in particular they are characterized by a high degree of rotational support. As we have shown, the angular momentum of infalling material provides a natural barrier to black hole growth, and so we would expect that rotationally supported systems to be more likely to be systems in which the central super-massive black hole is malnourished and underweight. Of course, the precise details of a galaxy’s assembly history are important but our model would predict a systematic offset between super-massive black hole masses in galaxies that have on average accreted higher angular momentum material than those that have on average accreted lower angular momentum material. In contrast, the Bondi–Hoyle model would predict that the black hole should continue to grow to a critical black hole mass imposed by the depth of the gravitational potential in which it sits, regardless of the angular momentum of infalling material. We shall investigate this question further in future work.

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