THE AGN–STARBURST CONNECTION, GALACTIC SUPERWINDS, AND $M_{\text{BH}} - \sigma$

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ABSTRACT

Recent observations of young galaxies at redshifts $z \sim 3$ have revealed simultaneous AGN and starburst activity, as well as galaxy-wide superwinds. I show that there is probably a close connection between these phenomena by extending an earlier treatment of the $M_{\text{BH}} - \sigma$ relation. As the black hole grows, an outflow drives a shell into the surrounding gas. This stalls after a dynamical time at a size determined by the hole’s current mass and thereafter grows on the Salpeter timescale. The gas trapped inside this bubble cools, forms stars, and is recycled as accretion and outflow. The consequent high metallicity agrees with that commonly observed in AGN accretion. Once the hole reaches a critical mass, this region attains a size such that the gas can no longer cool efficiently. The resulting energy-driven flow expels the remaining gas as a superwind, fixing both the $M_{\text{BH}} - \sigma$ relation and the total stellar bulge mass at values in good agreement with observations. Black hole growth thus produces starbursts and ultimately a superwind.

Subject headings: accretion, accretion disks — black hole physics — galaxies: formation — galaxies: nuclei — quasars: general

1. INTRODUCTION

Most astronomers now believe that the center of every galaxy contains a supermassive black hole (SMBH). There is a close observational correlation (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002) between the mass $M$ of this hole and the velocity dispersion $\sigma$ of the host bulge, which strongly suggests a connection between the formation of the black hole and of the galaxy itself.

There have been many attempts to explain this correlation theoretically. Some of these appeal to the ambient conditions in the host galaxy (Adams et al. 2001), accretion of collisional dark matter (Ostriker 2000), or star captures by the central accretion disc (Miralda-Escudé & Kollmeier 2005). A very large class of models (Silk & Rees 1998; Haehnelt et al. 1998; Blandford 1999; Fabian 1999; Wyithe & Loeb 2003; King 2003, hereafter K03; Murray et al. 2005; Sazonov et al. 2005; Robertson et al. 2005; Di Matteo et al. 2005; Begelman & Nath 2005) use the idea of feedback by a wind or outflow driven in some way by the accretion required to grow the central black hole. In this picture, the black hole eventually reaches a mass $M_{\text{BH}}$ such that further accretion (and thus growth of $M_{\text{BH}}$) is prevented because the outflow sweeps away the ambient gas.

This is a very natural idea, given that we know that most of the mass of the nuclear black holes is assembled by luminous accretion (Soltan 1982; Yu & Tremaine 2002). Moreover, the rate at which mass tries to flow in toward the central black hole in a galaxy is set by conditions far away, for example by interactions or mergers with other galaxies. These rates must be at least comparable to the instantaneous Eddington rates in order to produce the known black hole masses in the available time (particularly at higher redshifts). Since these external conditions cannot know what the current mass of the central black hole is, it seems very likely that super-Eddington conditions prevail for most of the time that the central black hole mass grows, and indeed this is what studies of the cosmological history of the process suggest (cf. Miller et al. 2005).

It is therefore reasonable to consider the effect on the host galaxy of such super-Eddington accretion. Simple theory (King & Pounds 2003) motivated by X-ray observations of outflows from bright quasars (e.g., Pounds et al. 2003a, 2003b; Reeves et al. 2003) suggests that the outflow momentum flux is comparable to that of the Eddington-limited radiation field, i.e., $M_{\text{out}}v = L_{\text{Edd}}/c$, where $M_{\text{out}}$ is the mass outflow rate and $L_{\text{Edd}}$ the Eddington luminosity, while the mechanical energy flux is $M_{\text{out}}v^2/2 = L_{\text{Edd}}/2M_{\text{out}}c^2$.

The wind from the central black hole sweeps up the surrounding gas into a shell. In a simple picture, no further accretion on to the black hole is possible once the shell has acquired the escape velocity $\sim \sigma$. The resulting theory then has no free parameter: remarkably, it leads to an $M - \sigma$ relation $M_{\text{BH}} \propto \sigma^4$, very close to the observed one ($M_{\text{bh}} \propto M_{200}^{3/2}$, with $M_{200} = M_{\text{BH}}/M_\odot$, $\sigma_{200} = \sigma/200$ km s$^{-1}$) in both slope and normalization (K03).

Recent observations prompt further checks of this simple model. Observations by Alexander et al. (2005) suggest that the growth of the black hole mass (revealed by AGN activity) occurs simultaneously with the formation of stars in the spheroid. Moreover, there is now suggestive evidence of very large-scale outflows from young galaxies at redshifts $z \sim 3$ (Wilman et al. 2005; see also Binette et al. 2000). A fuller treatment of the problem is therefore appropriate. I begin by considering the initial momentum-driven outflow in more detail.

2. BLACK HOLE GROWTH

We model a protogalaxy as an isothermal sphere of dark matter. If the gas fraction is $f_g = \Omega_{\text{gas}}/\Omega_{\text{matter}} = 0.16$ (Spergel et al. 2003), its density is $\rho = f_g \sigma^2/2\pi G r^2$, where $\sigma$ is assumed constant. The gas mass inside radius $R$ is

$$M(R) = 4\pi \int_0^R \rho r^2 dr = \frac{2f_g \sigma^2 R}{G},$$

so this is the mass of the shell of swept-up matter at radius $R$. Inside a certain radius $R_c$ (see below) the shocked wind can always cool, so we have an outflow driven by the momentum rate $M_{\text{out}}v = L_{\text{Edd}}/c$.

K03 simplified the problem by considering only the driving by this force, and asking under what conditions the resulting...
outflow velocity reaches the escape value \( \sim \sigma \). To follow the process in detail we must include the resistance by gravity. The equation of motion is

\[
\frac{d}{dt} [M(R) \dot{R}] + \frac{GM(R)[M + M(R)]}{R^2} = \frac{L_{\text{edd}}}{c};
\]

where \( M_\sigma = f g \kappa \pi G^2 \sigma \). From equation (3) we have \( \ddot{R} < 0 \) for \( M < M_\sigma \), i.e., the shell always decelerates.

Now let us consider the growth of the black hole mass \( M \). As argued above, this is likely to be super-Eddington at small \( M \) and set by conditions far from the hole. Thus any feedback ultimately limiting the growth of \( M \) can only occur when the bubble radius \( R \) is similarly large. This requires the wind outflow to be launched with at least the local escape velocity near the black hole. X-ray observations of outflows indeed suggest this (see the discussion in King & Pounds 2003). For \( R \gg GM/\sigma^2 \) we can neglect the black hole gravity term \( GM/R \) in equation (3). Then integrating twice gives

\[
\dot{R}^2 = \frac{2 \dot{R}_0^2}{2 \sigma^2 (1 - M/M_\sigma)} - \frac{2 \sigma^2 (1 - M/M_\sigma)}{\dot{R}} - \frac{2 \sigma^2 (1 - M/M_\sigma)}{\dot{R}} \dot{R},
\]

where \( \dot{R} = \dot{R}_0 \) at \( R = R_0 \), with \( R_0 \) some large radius. (One could in principle connect \( R_0, \dot{R}_0 \) to the initial conditions near the black hole by numerical integration of the full eq. [3], but this is unnecessary for our purposes.) We see that for \( M < M_\sigma \) the shell reaches a maximum radius \( R_{\text{max}} \) given by

\[
R_{\text{max}}^2 = 1 + \frac{\dot{R}_0^2}{2 \sigma^2 (1 - M/M_\sigma)}.
\]

after a dynamical time \( t_{\text{max}} = R_0 \dot{R}_0 / 2 \sigma^2 (1 - M/M_\sigma) \) before stalling. For consistency we require \( GM/R_{\text{max}} \ll \sigma^2 \), or that the swept-up mass \( M_{\text{max}} = M(R_{\text{max}}) = 2 \sigma^2 (1 - M/M_\sigma) \) be rather larger than the black hole mass.

Once the bubble reaches the mass \( M_{\text{max}}(M) \), the ram pressure of the outflow cannot sweep up any additional mass. Thus in particular the shocked wind gas cannot add to the shell, but must fall back and orbit as it cools. Some of this gas forms stars and begins to grow the spheroidal stellar component. Depending on how angular momentum is redistributed, some of the shocked wind gas is instead potentially available to continue refuelling the black hole, very possibly at a super-Eddington rate. Thus if \( M_{\text{acc}} \gg M_{\text{edd}} \), gas may be repeatedly recycled as outflow while the black hole mass \( M \) and the bubble radius \( R \) grow on the Salpeter timescale \( t_s = M/M_{\text{edd}} \), increasing \( M_{\text{max}}(M) \) on the same timescale. The most massive stars have lifetimes less than \( t_s \), so much of their gas, now enriched in metallicity, is returned to the ISM and is potentially available for feeding the hole once more.

The continuous compression and recycling occurring during the black hole growth must promote efficient star formation. Hence this picture indeed explains why AGN activity and starbursts are simultaneous, as in observations of SCUBA galaxies by Alexander et al. (2005). Moreover, it accounts for the high metallicity commonly observed in gas accreting in AGNs. If the supply of new gas for accretion (e.g., produced by merger events) is slow, star formation will deplete the gas supply to the point where accretion gradually shuts off. The swept-up gas (by now mostly turned into stars) must fall back, thus forming a spheroidal stellar bulge around the black hole. Such a galaxy would have \( M_{\text{BH}} \) lying below the \( M-\sigma \) relation, only growing toward it again as a new merger event supplies more mass.

3. The \( M-\sigma \) Relation

Given an adequate mass supply (e.g., by mergers), \( M \) grows on the Salpeter timescale as explained above. However the shell radius \( R_{\text{max}} \) gets very large (whatever the values of \( R_0 \) and \( R_0 \)) as \( M \) approaches the value where the denominator in equation (4) vanishes, i.e.,

\[
M_{\text{BH}} = \frac{f_g \kappa}{\pi G^2} \sigma^4
\]

where \( \kappa \) is the electron scattering opacity. In particular, at such masses \( R_{\text{max}} \) reaches the radius \( R_e \), at which Compton losses no longer cool the shocked wind efficiently (see K03). At this point the extra pressure accelerates the shell, so that it escapes the galaxy entirely (see below), thus finally shutting off accretion. Thus the black hole mass cannot grow beyond that given by equation (5), and this is the \( M-\sigma \) relation. The proportionality constant is twice that of the simple treatment in K03, but still well within observational scatter.

4. The Bulge Mass

If the shocked gas no longer efficiently cools, then the driving force on the shell is now the total gas pressure \( P \), which is larger than the ram pressure \( \rho_0^2 \) appearing in equation (2). The equation of motion thus has right-hand term \( 4 \pi R^2 P \) rather than \( L_{\text{edd}}/c. \)

We eliminate \( P \) by using the energy equation, allowing for the rate at which energy is fed into the shocked gas, minus the rate of work on the ambient gas and against gravity, and after some algebra we get

\[
\eta c \frac{L_{\text{edd}}}{2} = \frac{2 f \sigma^4}{G} \left( \frac{1}{2} R^2 \dot{R} + 3 R R \ddot{R} + \frac{3}{2} \dot{R}^2 \right) + 10 f) \sigma^4 \dot{R} R.
\]

where \( \eta = 0.1 \) is the accretion efficiency. Using \( M = M_{\text{BH}} \) from equation (5) in \( L_{\text{edd}} \), this has a solution \( R = v/f t \) with \( \eta c = 3 \sigma^4 f \rho_0^2 + 10 v_e \). The assumption \( v_e \ll \sigma \) leads to a contradiction \( v_e = 0.01 c \gg \sigma \); hence this equation has the approximate solution

\[
v_e = \left( \frac{2 \sigma^4 c}{3} \right)^{1/3} \approx 875 \sigma_{200}^{1/3} \text{ km s}^{-1}.
\]

Hence, the remaining gas outside \( R_c \) is driven off completely. The total gas mass turned into bulge stars is thus

\[
M_g = M(R_c) = 1.9 \times 10^{11} \sigma_{200}^{1/3} M_\odot \left( \frac{L}{e} \right)^{2/3} b^{-1} f_{\text{g}}^{3/2} M_\odot
\]

(from K03). As shown in K03, this stellar mass reproduces the approximate relation \( M_{\text{BH}} = 10^{-3} M_g \) (Magorrian et al. 1998; Merritt & Ferrarese 2001) if \( f_g, v_e \) and \( b \) all differ little between galaxies. The \( M_{\text{BH}}-M_g \) relation is known to be rather weaker than the \( M_{\text{BH}}-\sigma \) relation, suggesting that there is indeed some spread here. Equation (8) would give \( M_g \sim \sigma^4 \) if \( f_g, v_e \), and \( b \) were strictly the same for all galaxies, formally slightly in-
consistent with the Faber-Jackson relation. This again suggest these quantities vary somewhat between galaxies.

5. SUPERWINDS

We have seen that SMBH growth is likely to drive a bubble into the surrounding gas and initiate vigorous star formation. We noted above that the lifetime of massive stars is less than the Salpeter time, so the supernovae produced by these stars must drive vigorous mass loss from within the bubble. Moreover, equation (7) shows that once the black hole mass reaches the value given by the $M_\star$–$\sigma$ relation (eq. [5]), its Eddington luminosity can in principle blow away all the mass beyond the cooling radius. It is tempting to see this as the origin of some observed galaxy-wide superwinds.

In particular, it is worth noting that superwind driving by outflows from SMBH as discussed here is more energy-efficient than the conventional picture of supernova driving. Thus in the example discussed by Wilman et al. (2005) the shell has mass $\sim 10^{11} M_\odot$ and velocity $\sim 250$ km s$^{-1}$ and hence kinetic energy $\sim 6.3 \times 10^{58}$ ergs. Supernovae provide $\sim 10^{50}$ ergs over $10^8$ yr. However, the superwind is expected to cool from the shock temperature $\sim 10^7$ K to a few $\times 10^5$ K, in photoionization equilibrium with the metagalactic ultraviolet radiation field, as it sweeps up the intergalactic medium around the original host galaxy. It thus becomes momentum-driven once again. This means that the conversion of supernova input energy to kinetic energy is likely to be much lower than the required 6.3%. By contrast, the Eddington momentum flux $L_{\text{Edd}}/c$ for an $\sim 10^6 M_\odot$ black hole operating for $\sim 10^8$ yr would provide a total momentum a few times $10^{51}$ g cm s$^{-1}$, very close to the estimated value.

This paper shows that SMBH growth simultaneously produces starbursts and strong outflows. Both are agents of mass loss, but the second is much more efficient than the first. Thus it may be worth looking for signs of obscured AGN activity where superwinds are seen and the accompanying starburst does not seem sufficient to drive them.

6. DISCUSSION

I have studied the feedback probably responsible for the $M_\text{hi}$–$\sigma$ relation in greater detail than in K03. In particular, I allow for the effects of gravity in slowing and ultimately stalling the swept-up shell of matter around the growing black hole. The gas trapped within this stalled bubble is efficiently turned into stars and can be recycled for accretion and outflow, enhancing its metallicity as it does so. The bubble radius grows initially on a dynamical timescale until it stalls, and then on the Salpeter timescale of the central black hole. Once the bubble reaches the radius where it can no longer efficiently cool, it carries away the gas further out in a fast, energy-driven flow.

This simple picture accounts for a number of things. The stellar bulge mass is the gas mass within the cooling radius, and agrees with the $M_\text{hi}$–$M_\bullet$ relation. The $M_\sigma$–$M_\bullet$ relation follows because the black hole cannot be efficiently fuelled once it is established. The simultaneous growth of the stellar and black hole masses agrees with the observed AGN–starburst connection. The gas accreting in AGNs must have high metallicity because it is trapped in the stalled bubble and repeatedly recycled through stars. Finally, the energy-driven outflow ending black hole growth suggests an explanation for galaxy-wide superwinds where high efficiency is indicated.

Clearly the approach taken here is extremely simplified. In particular, a fuller picture requires a better description of how ambient gas loses enough angular momentum to accrete on to the central black hole.

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