Black holes, cuspy atmospheres, and galaxy formation

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In cuspy atmospheres, jets driven by supermassive black holes (BHs) offset radiative cooling. The jets fire episodically, but often enough that the cuspy atmosphere does not move very far towards a cooling catastrophe in the intervals of jet inactivity. The ability of energy released on the sub-parsec scale of the BH to balance cooling on scales of several tens of kiloparsecs arises through a combination of the temperature sensitivity of the accretion rate and the way in which the radius of jet disruption varies with ambient density. Accretion of hot gas does not significantly increase BH masses, which are determined by periods of rapid BH growth and star formation when cold gas is briefly abundant at the galactic centre. Hot gas does not accumulate in shallow potential wells. As the Universe ages, deeper wells form, and eventually hot gas accumulates. This gas soon prevents the formation of further stars, since jets powered by the BH prevent it from cooling, and it mops up most cold infalling gas before many stars can form. Thus BHs set the upper limit to the masses of galaxies. The formation of low-mass galaxies is inhibited by a combination of photo-heating and supernova-driven galactic winds. Working in tandem these mechanisms can probably explain the profound difference between the galaxy luminosity function and the mass function of dark halos expected in the cold dark matter cosmology.

Keywords: Cooling flows – galaxies: nuclei – galaxies: formation – galaxies: jets – galaxies: luminosity function

1. Introduction

Gravitational potential wells that are deep enough to trap gas hotter than \( \sim 3 \times 10^6 \text{K} \) can generally be detected in the thermal X-ray emission of the trapped gas. These potential wells range in size from those of massive elliptical galaxies through groups of galaxies to clusters of galaxies. As one proceeds down this sequence, the fraction of the system’s baryons that are contained in the virial-temperature gas rises from \( \lesssim 10\% \) to \( \gtrsim 80\% \).

The central cooling time \( t_c(0) \) is defined to be the ratio of the central energy density to the central luminosity density due to radiative cooling. In many, perhaps most, systems, \( t_c(0) \) is shorter than the Hubble time. In the case of an elliptical galaxy such as NGC 4472, \( t_c(0) \approx 0.3 \text{Myr} \), while in a cluster of galaxies such as Hydra \( t_c(0) \approx 300 \text{Myr} \). Hence, we must ask how these systems endure for times that greatly exceed \( t_c(0) \).

In the absence of heating, radiative losses cause the central density to rise inexorably as the central temperature falls. The density reaches arbitrarily large values in a time \( t \) that is slightly shorter than \( t_c \) (Murray & Balbus, 1992). Kaiser & Bin-
ney (2003) present a semi-analytic model of this process, which ends in a ‘cooling catastrophe’.

The XMM-Newton and Chandra satellites have established two facts for which there was sketchy evidence in earlier data. First, although the temperature drops as one approaches the centre of one of these systems, it is bounded below by a ‘floor’ temperature $\sim \frac{1}{3} T_{\text{vir}}$, where $T_{\text{vir}}$ is the ‘virial temperature’ characteristic of the bulk of the X-ray emitting gas. Second, the X-ray emitting plasma is clearly being heated by outflows from a centrally located active galactic nucleus that is surely an accreting black hole (BH). These facts have greatly strengthened the case that in the long run the energy radiated by the hot gas is replaced by energy released by accretion of gas onto the BH. Consequently, in these systems gas is neither cooling nor flowing inwards as has traditionally been supposed, and their established designation as ‘cooling flows’ is unfortunate. A more appropriate name is ‘cuspy atmosphere’ since the defining characteristic of these systems is a sharply peaked X-ray surface-brightness profile, which proves to be associated with a central depression in the temperature of the gas.

Many questions about cuspy atmospheres remain open. These include (1) the mechanism by which energy is transported from the solar-system scale of the BH to the 10 to 1000 kpc scale of the thermal plasma, and (2) the timescale between eruptions of the BH and the corresponding depth of the excursions in the central density of the cuspy atmosphere.

2. Time between eruptions

Two extreme views are possible on this second point. A violent outburst of the BH might stir the trapped gas into something approaching an adiabatic atmosphere – one in which the specific entropy $s$ is everywhere the same. If heating then stops completely, the specific entropy profile $s(r)$ steepens as the system drifts towards a cooling catastrophe, at which another violent outburst of the BH reheats to a state of near-uniform $s$ (Kaiser & Binney 2003). In this picture, systems such as Hydra and Virgo are observed $\sim 300$ Myr before their next cooling catastrophe. The opposite extreme was explored by Tabor & Binney (1993), who conjectured that steady central heating generates a uniform-entropy core, which gradually expands as material falls into it at the base of an enveloping cuspy atmosphere.

Observations cast doubt on this last picture in two ways. First, cuspy atmospheres appear not to have adiabatic cores (Kaiser & Binney 2003). Second, there is much evidence that BHs eject energy in discrete bursts rather than continuously.

The absence of adiabatic cores is a clue to the way in which BHs heat the system. If photons carried the energy from the relativistic region, the energy would be thermalized deep down and then convected outwards, as it is in a late-type star with a convective core. If jets carry the energy away from the BH, it will thermalize over a wide range of radii, including radii in excess of the $>100$ kpc scale of the cuspy atmosphere. So with jet heating an adiabatic core need not arise (Binney & Tabor 1995).

The most relevant evidence for discrete bursts of heating also confirms that jets are the intermediaries: we see ‘cavities’ or ‘bubbles’ in the X-ray emitting plasma that are surely inflated where a jet is disrupted as it impacts the denser thermal plasma. Several systems show more than one generation of cavity, and the cavities...
Table 1. Parameters for five clusters with cavities.

| system  | $PV_{10^{58}\text{erg}}$ | $L_X_{10^{43}\text{erg s}^{-1}}$ | $\tau_{\text{Myr}}$ | reference               |
|---------|---------------------------|--------------------------------|---------------------|-------------------------|
| Hydra A | 27                        | 30                             | 88                  | McNamara et al. 2000,   |
|         |                           |                                |                     | Nulsen et al. 2002      |
| A2052   | 4                         | 3.2                            | 122                 | Blanton et al. 2001     |
| Perseus | 8                         | 27                             | 29                  | Fabian et al. 2000,     |
|         |                           |                                |                     | Allen et al. 1992       |
| A2597   | 3.1                       | 3.8                            | 79                  | McNamara et al. 2001    |
| A4059   | 22                        | 18                             | 119                 | Huang & Sarazin 1998,   |
|         |                           |                                |                     | Heinz et al. 2002       |

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Table 1 illustrates this point by giving for five clusters an estimate of pressure times volume for a pair of cavities, the X-ray luminosity of the cuspy atmosphere $L_X$ (mostly from the classic $\dot{M}$ value) and the characteristic time $\tau = \frac{3PV}{L_X}$. The minimum work done by an AGN in blowing a cavity is $\frac{3}{2}PV$, rising to $4PV$ if the fluid within the cavity is relativistic. Since the inflation of cavities is likely to be highly irreversible, especially in its early stages and from the perspective of the ambient medium, the actual work done will be larger. If we conservatively assume that the work done is $3PV$, then heating will balance cooling if the intervals between the creation of cavities equals the quantity $\tau$ listed in table 1. These intervals agree to within the errors with the values estimated from hydrodynamic models.

3. The coupling between BH and X-ray atmosphere

The suggestion that heating balances cooling is puzzling for two reasons. First, there is much evidence BHs release energy very unsteadily, and second because there is a nearer the BH are younger and thus more luminous in synchrotron radiation from extremely energetic electrons ($\gamma \gtrsim 10^5$). It is generally agreed that these cavities move outwards at approximately the speed of sound ($\sim 1000 \text{km s}^{-1}$) in the ambient plasma (Gull & Northover 1973; Churazov et al. 2001; Quilis et al. 2001; Brüggen & Kaiser 2001, 2002; Brüggen et al. 2002).

Does trapped virial-temperature gas drift far towards a cooling catastrophe during inter-outburst intervals, so that it must be radically restructured during an outburst? The rate of evolution of the density profile of X-ray emitting gas accelerates slowly at first, and very rapidly towards the end of a drift to a cooling catastrophe. Hence, if most sources are drifting towards the next cooling catastrophe, many sources will be seen in configurations near those produced by an outburst, and only a few sources will be found close to a cooling catastrophe. From the fact that $\gtrsim 70\%$ of X-ray clusters have cusped cooling cores in which cooling times $\lesssim 1 \text{Gyr}$ occur (Peres et al. 1998), it follows that near-adiabatic states are not produced by outbursts, and the time between outbursts is $\lesssim 1 \text{Gyr}$. Kaiser & Binney (2003) concluded that the scarcity of gas at $\lesssim \frac{1}{3}\sqrt{T_{\text{vir}}}$ is compatible with the sources cycling between the least centrally concentrated configurations observed and cooling catastrophes.

However, the data do not require such deep cycles. The sizes and locations of cavities in clusters such as Perseus (Fabian et al. 2000), MKW3s (Mazzotta et al. 2002) and Abell 2597 (McNamara et al. 2001) suggest that a new pair of cavities is produced every $\lesssim 50 \text{Myr}$, and simple estimates of the energy injected into the thermal plasma over the lifetime of a cavity (Churazov et al. 2002) suggest that in this case heating by the BH can balance radiative cooling. Table 1 illustrates this point by giving for five clusters an estimate of pressure times volume for a pair of cavities, the X-ray luminosity of the cuspy atmosphere $L_X$ (mostly from the classic $\dot{M}$ value) and the characteristic time $\tau = \frac{3PV}{L_X}$. The minimum work done by an AGN in blowing a cavity is $\frac{3}{2}PV$, rising to $4PV$ if the fluid within the cavity is relativistic. Since the inflation of cavities is likely to be highly irreversible, especially in its early stages and from the perspective of the ambient medium, the actual work done will be larger. If we conservatively assume that the work done is $3PV$, then heating will balance cooling if the intervals between the creation of cavities equals the quantity $\tau$ listed in table 1. These intervals agree to within the errors with the values estimated from hydrodynamic models.
The gross mismatch between the 50 to 500 Myr timescale on which the thermal plasma adjusts its configuration and the ≲ 10 yr timescale on which the energy output of massive BHs is known to change by factors of 2. So what mechanisms could enable a BH to hold fairly constant the density profile in the vastly bigger atmosphere of X-ray emitting gas?

(a) Bondi accretion

One condition for establishing a steady state is that the energy output of the BH should increase when the cuspy atmosphere’s central density increases, and do so with a delay that is small compared to the central cooling time ∼ 100 Myr. The Bondi radius $r_{\text{Bondi}}$ is the distance from the BH at which the BH’s Kepler speed equals the sound speed. In the cases of Sgr A* at the centre of the Galaxy and of M87, $r_{\text{Bondi}}$, which bounds the BH’s sphere of influence, is resolved by Chandra. Hence we can be pretty certain of the rate at which gas flows into the sphere of influence. Gas with temperature $T_0$ flows at the sound speed $c_s$ through the spherical surface of area

$$A = 4\pi \left( \frac{GMm_p\alpha}{k_B T_0} \right)^2,$$

(3.1)

where $\alpha = \frac{3}{5} \mu$, with $\mu = 0.62$ the molecular weight. The particle density is $n \approx P/k_B T_0$, where $P$ is the pressure just above the surface. Hence, the accretion rate

$$\dot{M} \approx n \mu m_p A c_s \approx 7\pi P (GM)^2 \left( \frac{\alpha m_p}{k_B T_0} \right)^{5/2},$$

(3.2)

rises at least as fast as $T_0^{-5/2}$, and any drop in $T_0$ will quickly lead to an increase in the BH’s power output. The luminosity of the cooling core is

$$L = \int d^3x \ n^2 \Lambda(T) \approx \int d^3x \left( \frac{P}{k_B T} \right)^2 \Lambda,$$

(3.3)

which has a very similar dependence on $T_0$ when one takes into account the tendency of $P$ to rise slightly as $T_0$ declines. Hence the mass falling into the sphere of influence during an outburst is expected to be roughly proportional to the energy radiated by the thermal plasma in the cooling core.

We are unsure what fraction of the material that enters the sphere of influence is accreted by the BH rather than being blown out in a wind or jet. How much energy is released when a given mass of gas is swallowed by the BH is also controversial. Fortunately observations of the best observed system suggest resolutions of these questions.

In M87 the Bondi accretion rate (3.2) is 0.1 $M_\odot \, \text{yr}^{-1}$, which yields a luminosity $5 \times 10^{44} \, \text{erg s}^{-1}$ if $0.1mc^2$ of energy is released for accretion of mass $m$ onto the BH (Di Matteo et al. 2003). The X-ray luminosity from the central ∼ 20 kpc of the cuspy atmosphere is $10^{43} \, \text{erg s}^{-1}$ (Nulsen & Böhringer 1995), while that of the AGN is $< 5 \times 10^{40} \, \text{erg s}^{-1}$. Estimates of the mechanical luminosity of the jet that emerges from the AGN range from $10^{43} \, \text{erg s}^{-1}$ (Reynolds et al 1996) to $10^{44} \, \text{erg s}^{-1}$ (Bicknell & Begelman 1999; Owen et al 2000). Thus the data for M87 suggest that the BH is accreting at a substantial fraction of the Bondi rate, and that the energy
released is passing along the jets to reheat the cuspy atmosphere on 10 kpc-scales. Radiative losses near the BH are negligible. This is precisely the situation envisaged by Binney & Tabor (1995).

Material that falls into the sphere of influence is likely to form an accretion disk or torus. In the case of M87, a disk of ionized gas has actually been seen with HST (Harms et al. 1994). The accretion disk will introduce a lag between a drop in the central temperature of the cuspy atmosphere and an increase in the power of the BH equal to the time it takes material to spiral through the disk. If this delay exceeded \( \sim 50 \) Myr, large-amplitude feedback oscillations would probably occur. Evidence that cuspy atmospheres are in near steady-states therefore suggests that material either accretes directly from the Bondi flow, or spirals through the accretion disk in \( \lesssim 50 \) Myr.

(b) Fixing the radial density profile

For a steady state to be reached, the radial profile of energy deposition by the jets at outburst must coincide with the radial profile of radiative losses between outbursts. Energy is transferred from a jet to the ambient plasma when the latter disrupts the jet, either in part or totally, as at the hot spot of a Fanaroff–Riley (FR) II radio source. The more powerful a jet is, the further out it will go before it is strongly disrupted. So the fraction of a jet’s energy that is deposited at large radii should increase with jet power. Conversely, the higher the ambient density is near the BH, the smaller will be the radii at which a given jet is disrupted and its energy thermalized.

Motivated by these considerations, Omma & Binney (2004) repeatedly simulated the dynamical evolution of cluster gas from an initial state that resembles the current state of the Hydra cluster. Each simulation was fully three-dimensional and used the adaptive-mesh code ENZO (Bryan 1999). The rate of radiative cooling was calculated for an optically thin plasma in thermal equilibrium. Hence a cooling catastrophe arose in the absence of jet heating.

In simulation 1 the jets fire after 262 Myr of cooling. They have a total power of \( 5 \times 10^{44} \) erg s\(^{-1}\) and run for 25 Myr, during which time they inject \( 4 \times 10^{59} \) erg. The jets in simulation 2 fire after 300 Myr of cooling, by which time an extra \( 4 \times 10^{59} \) erg has been lost to radiation, and they inject \( 8 \times 10^{59} \) erg at \( 10^{45} \) erg s\(^{-1}\). Thus the later ignition of the jets in simulation 2 is compensated for by enhanced energy injection along the lines suggested by the model of Bondi accretion.

It is instructive to compare these energies with what would be available through Bondi accretion onto a BH of mass \( M \) under the assumption that accretion of mass \( m \) by the BH releases \( 0.1mc^2 \) of energy. If the atmosphere were isothermal in the numerically unresolved region from a radius 1 kpc to the BH’s radius of influence, the energy available from Bondi accretion would be \( E = 5(M/10^9 M_\odot)^2 \times 10^{59} \) erg over 262 Myr, and \( 7(M/10^9 M_\odot)^2 \times 10^{59} \) erg over 300 Myr. Thus for black hole masses \( \sim 3 \times 10^9 M_\odot \) of the expected order, \( \sim 10\% \) of what flows into the BH’s sphere of influence needs ultimately to be accreted by the BH. For a BH of this mass the BH’s mechanical luminosity in simulation 1 is \( 7 \times 10^{-4} L_{\text{Edd}} \), where \( L_{\text{Edd}} \) is the Eddington luminosity at which free-electron scattering causes radiation pressure to balance gravity.

In figure 1 the dotted curve shows the density profile of the cluster gas at the
Figure 1. Dotted curve: initial density profile of all simulations. Data points: density in Hydra from David et al. (2000). Curves labelled $t = 0$: densities after cooling and immediately before jet ignition in simulation 1 (full curve) and simulation 2 (dashed curve). Bottom curves show spherically averaged density profiles 42 Myr after ignition in simulation 1 (full) and simulation 2 (dashed).

start of both simulations. The data points show the density in the Hydra cluster as deduced by David et al. (2000). The upper full curve shows the density profile at the ignition of the jets in simulation 1, while the dashed curve labelled $t = 0$ shows the density profile at the ignition of the jets in simulation 2. The effect on the density profile of $\sim 300$ Myr of passive cooling is evident. The bottom full curve shows the spherically averaged density profile 42 Myr after the firing of the jet in simulation 1, while the bottom dashed curve shows the same data for simulation 2. At that time, 17 Myr after the jets extinguished, the curves are quite similar to the initial profile and the data. Thus in both simulations the injected energy has effectively reversed the effect of 300 Myr of cooling.

Most crucially, the dashed curve of simulation 2 now lies below the full curve, implying that the system that cools for longer and has the most centrally concentrated density profile when its jets ignite, ends up with the less centrally concentrated profile. The density profiles at times later than those shown in figure 1 confirm that the greater central concentration of simulation 1 at $t = 42$ Myr is not an aberration: the profile for simulation 1 remains on top of that of simulation 2, and moves upwards faster. Consequently, when the profiles are next similar to those labelled $t = 0$ in figure 1, we can expect simulation 1 to be the scene of the more energetic outburst slamming into the more centrally concentrated ICM. When the dust settles after this second outburst, the profile of simulation 2 will be the more centrally concentrated and the pair of simulations will have come full cycle. Hence these simulations suggest that the density profiles of cuspy-atmosphere clusters are oscillating around an attracting profile.

4. Impact on galaxy formation

It has long been suggested that the cuspy-atmosphere phenomenon is fundamental for the galaxy-formation process (e.g., Fabian 1994). I agree, but I want to persuade
you that cuspy atmospheres do not tell us how galaxies formed, but why they ceased forming (Binney 2004).

The standard picture of galaxy formation starts from the assumption that when gas falls into a potential well, it shock heats to the virial temperature (Rees & Ostriker 1977; White & Rees 1978). There is increasing evidence that this assumption is significantly misleading: only a fraction of infalling gas is heated to the virial temperature, and this fraction is large only for potential wells that are deeper than those associated with galaxies (Binney 1977; Katz et al. 2003; Birnboim & Dekel, 2003). On account of the shape of the cooling curve of optically thin plasma, the temperature of infallen gas is bimodal. It seems likely that stars form from a fraction of the cold gas, and energy released by these stars strongly heats the remaining gas. If the potential well has a virial velocity below \( \sim 100 \text{ km s}^{-1} \) (roughly that of an \( L^* \) galaxy), the heated gas flows out of the potential well and star formation ceases until more cold gas can fall in. Through repeated accretion of cold gas, a disk galaxy slowly builds up. A merger may convert this to an early-type galaxy, but subsequent infall of cold gas and star formation can restore its status as a disk galaxy.

Through mergers and gas accretion, the depth of the potential well increases. When its virial velocity reaches \( \sim 100 \text{ km s}^{-1} \), gas heated by star formation can no longer be driven out (Dekel & Silk, 1986). Consequently, an atmosphere of virial-temperature gas builds up. Such atmospheres have been called a cooling flows because their central cooling times are short. Actually the temperature of such a system is thermostatically controlled by the nuclear BH, which grew to its current size during merging episodes as large quantities of cold gas were driven to the centre, stimulating bursts of star formation, and permitting the BH to gorge itself at \( L_{\text{Edd}} \).

As the density and temperature of the virial-temperature atmosphere increases, the environment becomes hostile to cold gas: filaments of infalling cold gas are shredded by Kelvin-Helmholtz instability and evaporated by electron conduction (Nipoti & Binney, 2004). This evaporation of cold gas can happen far from the BH, although the energy required to heat the cold gas ultimately comes from the BH, which underwrites the atmosphere’s temperature. The elimination of filaments of infalling cold gas gradually throttles star formation, because the hot atmosphere never produces cold gas: the coldest part of the atmosphere surrounds the BH, and energy released by the BH reheat it long before it can reach the kinds of temperatures (\( \lesssim 30 \text{ K} \)) at which stars can form. The effect of the hot atmosphere on the star-formation rate is not sudden, however, because a sufficiently massive filament on a sufficiently low-angular-momentum orbit can always get through to the atmosphere’s cooling core, where it can survive thermal evaporation for a significant time and lead to the formation of some stars. In the centres of clusters such as Perseus we see such filaments and infer that they have embedded star formation (McNamara et al. 1996; Conselice et al. 2001; Fabian et al. 2003). These filaments have often been supposed to have formed through catastrophic cooling of the hot atmosphere, but their dust content and morphology are more consistent with the infall hypothesis (Soker et al. 1991; Sparks et al. 1989; Sparks 1992).

The galaxy luminosity function differs profoundly from the mass function of dark-matter halos in all cold-dark matter (CDM) cosmogonies. Specifically, there are both fewer faint galaxies than low-mass halos, and fewer luminous galaxies than high-mass halos. The dearth of low-luminosity galaxies can be plausibly ascribed to
the effects of photoionization at redshifts $z \lesssim 20$ (Efstathiou 1992, Dekel 2004) and to the ability mentioned above, of star formation to heat residual gas and drive it out of shallow potential wells. In a recent examination of this problem in the context of semi-analytic galaxy formation models, Benson et al. (2003) found that when feedback was strong enough to make the number of low-luminosity galaxies agree with observation, too many high-luminosity objects formed because gas ejected from shallow potential wells later fell into deep potential wells. The crucial ingredients missing from the Benson et al. models are (a) the ability of the central black hole to prevent cooling of virial-temperature gas, and (b) the infall of cold gas, together with the tendency of a hot atmosphere to destroy filaments of cold infalling gas.

(a) History of BH growth

The demography of quasars and radio galaxies indicates that most of the energy released in the formation of a massive BH has emerged in bursts of accretion that have driven the luminosity to near $L_{\text{Edd}}$. Thus Yu & Tremaine (2002) found that the total energy emitted in the optical and UV bands by AGN lies remarkably close to the energy released in the growth of massive BHs. They also showed that a high efficiency $\epsilon \gtrsim 0.1$ for the conversion of accretion energy to optical/UV photons and radiation at $L \simeq L_{\text{Edd}}$ must be assumed if the formation of the known population of BHs is to generate as many luminous quasars as are observed. The mass of a BH that radiates at $L_{\text{Edd}}$ exponentiates on the Salpeter time $t_{S} \simeq 2.5 \times 10^{7}(0.1/\epsilon)$ yr. If BHs form with masses $M \sim 10^{3} M_{\odot}$, then they require $\sim 14t_{S}$ to grow to their current $M \sim 10^{9} M_{\odot}$. Thus Yu & Tremaine require them to have radiated at $\sim L_{\text{Edd}}$ for $\sim 0.4$ Gyr and accreted at $\lesssim 0.05L_{\text{Edd}}$ for the remaining 13 Gyr.

The tight correlation between BH mass and the velocity dispersion of the host spheroid tells us that BH growth is dominated by periods of rapid formation of spheroid stars. This conclusion is reinforced by the similarity in time and space of the densities of luminous quasars and luminous star-forming galaxies. It seems clear that these episodes of rapid BH and spheroid growth occur when there is plenty of cool gas at the galaxy centre. These episodes are short because a combination of star formation, aided by radiation from the BH (OSTRIKER), and mass loss in a galactic wind, quickly lowers the gas density to the point at which it can be heated to $\sim 3 \times 10^{6}$K. Star formation and BH growth then all but cease. The hot gas flows out of shallower potential wells, but is confined by wells with virial velocities $\gtrsim 100$ km s$^{-1}$.

Once the host potential is deep enough to trap supernova-heated gas, and a hot atmosphere builds up, the BH becomes more regularly active. Its mode of operation changes significantly, in the sense that its energy output becomes predominantly mechanical. In general terms it is natural that photons should diminish in prominence as distributors of the BH’s energy production once the BH starts accreting optically thin, virial-temperature gas. But this mode switch has yet to be properly understood. Observations of M87 leave no doubt that the switch occurs, however.

The rate at which the BH’s mass grows in the new regime is determined by the rate at which the cuspy atmosphere radiates, which for a typical cluster lies in the range $10^{43}$ to $10^{44}$ erg s$^{-1}$. At the canonical 10% accretion efficiency, these luminosities imply mass accretion rates $\dot{M} \sim 0.02$ to $0.002 M_{\odot}$ yr$^{-1}$. Growth at rates of this order for $10^{10}$ yr does not have a significant impact on the mass of a

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BH that already contains $>10^9\,\text{M}_\odot$. This is why the combined radiative output of quasars already accounts for the observed BH mass density.

Fresh supplies of cold gas can revive star formation. If the gas has high angular momentum and accumulates in a disk, there can be significant star formation without enhanced BH growth. Gas infall enhances BH growth only if the gas tumbles to the galactic centre to form spheroid stars. Hence the BH’s mass is correlated with the properties of the spheroid rather than with those of the whole galaxy.

5. Conclusions

Although some loose ends remain, I am impressed by the way in which disparate strands of theory and observation are coming together to form a coherent picture of galaxy formation, and the symbiosis of BHs with spheroids and cuspy atmospheres. In this picture BHs play a major role in preventing gas that is heated to the virial temperature from cooling. Galaxies that are in potential wells deep enough to trap supernova-heated gas soon cease to form stars, even from cold infalling gas of high angular momentum, because trapped gas at the virial temperature evaporates infalling gas before stars can form from it. Hence BHs cause the cutoff above $L_*$ in the galaxy luminosity function.

BHs are effective thermostatic heaters for two reasons. First, they sample the coldest gas, and the rate at which they are fed increases rapidly as the temperature of this gas falls. Moreover, the mass accreted in any time interval is roughly proportional to the energy radiated by the central part of the atmosphere in that interval. Second, they inject energy through jets, and the radial range over which a jet’s energy is thermalized is smaller when the pre-outburst atmosphere is more centrally concentrated. This phenomenon causes the density profile of an atmosphere to fluctuate around an attracting profile that appears to be similar to those observed.

For more than two decades the theory of steady-state cooling flows with mass dropout held up progress in appreciating the role that AGN play in structuring galaxies. This theory was finally swept away by damning evidence from the Chandra and XMM-Newton missions, but its internal contradictions should have left it without proponents a decade ago. Meanwhile, evidence has emerged for the intimate connection between BHs and both quasars and spheroids, and for the strength of mass outflows from star-forming galaxies. The last piece of the jigsaw that gives a coherent picture of galaxy formation is the still tentative evidence for the importance of cold infall.

Over the next decade I hope that this picture will be consolidated by understanding (a) the relation between extra-planar gas around spiral galaxies and the infall and outflow phenomena, and (b) why BH accretion sometimes produces the Eddington luminosity and rapid BH growth, and in other circumstances yields jets with high efficiency. Finally, we must come to an understanding of how it is that infalling cold gas frequently has enough angular momentum to form a galactic disk.

References

Allen, S. W., Fabian, A. C., Johnstone, R. M., Edge, A. C. & Nulsen, P. E. J. 1992 MNRAS, 254, 51

Article submitted to Royal Society
Benson, A. J., Bower, R. G., Frenk, C. S., Lacey, C. G., Baugh, C.M. & Cole S. 2003, ApJ, 599, 38
Bicknell G. V. & Begelman, M. C. 1999 in The radio galaxy M87 (eds H. J. Roser & K. Meisenheimer) Berlin: Springer
Binney, J. 1977 ApJ, 215, 483
Binney, J. 2004 MNRAS, 347, 1093
Binney, J. & Tabor, G. 1995 MNRAS, 276, 663
Birnboim, Y. & Dekel, A. 2003 MNRAS, 345, 349
Blanton, E. L., Sarazin, C. L., McNamara, B. R. & Wise, M. W. 2001 ApJ, 558, L15
Brüggen, M. & Kaiser, C. R. 2001 MNRAS, 325, 676
Brüggen, M. & Kaiser, C. R. 2002 Nature 418, 301
Brüggen, M., Kaiser, C. R., Churazov, E. & Ensslin, T. A. 2002 MNRAS 331, 545
Bryan, G. L. 1999 Comp. Sci. Eng., 1:2, 46
Churazov, E., Brüggen, M., Kaiser, C. R., Böhringer, H. & Forman, W. 2001 ApJ, 554, 261
Churazov, E., Sunyaev, R., Forman, W. & Böhringer, H. 2002 MNRAS, 332, 729
Conselice, C. J., Gallagher, J. S. & Wyse, R. F. G. 2001 AJ, 122, 2281
David, L. P., Nulsen, P. E. J., McNamara, B. R., Forman, W., Jones, C., Ponman, T., Robertson, B. & Wise, M. 2001 ApJ, 557, 546
Dekel, A. 2004 astro-ph/0401503
Dekel, A. & Silk, J. 1986 ApJ, 303, 39
Di Matteo, T., Allen, S. W., Fabian, A. C., Wilson, A. S. & Young A. J. 2003 ApJ, 582, 133
Efstathiou, G., 1992, MNRAS 256, 43P
Fabian, A. C. 1994 ARAA 32, 277
Fabian, A. C. et al. 2000 MNRAS, 318, L65
Fabian, A. C. et al. 2003 MNRAS, 344, L8
Gull, S. F. & Northover, K. J. E. 1973 Nature, 244, 80
Harms, R. J. et al. 1994 ApJ, 435, L35
Heinz, S., Choi, Y.-Y., Reynolds, C. S. & Begelman, M. C. 2002 ApJ, 569, L79
Huang, Z. & Sarazin, C. L. 1998 ApJ, 496, 728
Kaiser, C. R. & Binney, J. 2003 MNRAS, 338, 837
Katz, N., Keres, D., Davé, R. & Weinberg, D. H. 2003 in The IGM/galaxy connection: the distribution of baryons at z = 0, ASSL Conference Proceedings Vol. 281, (eds J. L. Rosenberg & M. E. Putman), Kluwer, Dordrecht, p. 185
Mazzotta, P. et al. 2002 ApJ, 567, 37
McNamara, B. R., O’Connell, R. W. & Sarazin, C. L. 1996 AJ, 112, 9
McNamara, B. et al. 2000 ApJ, 534, L135
McNamara, B. et al. 2001 ApJ, 562, L149
Murray, S. D. & Balbus, S. A. 1992 ApJ, 395, 99
Nipoti, C. & Binney, J. 2004 MNRAS, in press (astro-ph/0401106)
Nulsen, P. E. J. & Böhringer, H. 1995 MNRAS, 274, 1093
Nulsen, P. E. J., David, L. P., McNamara, B. R., Jones, C., Forman, W. R. & Wise, M. 2002 ApJ, 568, 163
Omma, H. & Binney, J. 2004 MNRAS in press (astro-ph/0312658)
Owen, F. N., Eilek, J. A. & Kassim, N. E. 2000 ApJ, 543, 611
Peres, C. B., Fabian, A. C., Edge, A. C., Allen, S. W., Johnstone, R. M. & White, D. A. 1998 MNRAS, 298, 416
Quilis, V., Bower, R. G., & Balogh, M. L. 2001 MNRAS, 328, 1091

Article submitted to Royal Society
Rees, M. J. & Ostriker, J. P. 1977 MNRAS, 179, 541
Reynolds, C. S., Di Matteo, T., Fabian, A. C., Hwang, U. & Canizares, C. R. 1996 MNRAS, 283, L111
Soker, N., Bregman, J. N. & Sarazin, C. L. 1991 ApJ, 368, 341
Sparks, W. B. 1992 ApJ, 399, 66
Sparks, W. B., Macchetto, F. & Golombek, D. 1989 ApJ, 345, 153
Tabor, G. & Binney, J. 1993 MNRAS, 263, 323
White, S. D. M. & Rees, M. J. 1978 MNRAS, 183, 341
Yu, Q. & Tremaine, S. 2002 MNRAS, 335, 695