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Supermassive Black Holes in Elliptical Galaxies: Switching from Very Bright to Very Dim

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ABSTRACT
Relativistic outflows (mainly observed in the radio) are a characteristic feature of both Galactic stellar mass black holes and supermassive black holes (SMBHs). Simultaneous radio and X-ray observations of Galactic sources have shown that the outflow is strong at low accretion rates, but it weakens dramatically or disappears completely at high accretion rates, manifesting structural changes in the accretion flow. It is reasonable to assume that SMBHs follow the same trend. For low luminosity SMBHs in nearby elliptical galaxies and clusters, recent observations strongly suggest that the outflows play the central role in keeping the gas hot (mechanical feedback). If the outflow is quenched in SMBHs at high accretion rates similarly to the behavior of galactic sources, then the straightforward consequence is a relatively weak feedback of rapidly accreting SMBHs. We argue that elliptical galaxies and their central engines should then evolve through two stages. Early on, the central SMBH rapidly grows by accreting cooling gas at a near-Eddington rate with high radiative efficiency but with weak feedback on the infalling gas. This stage terminates when the black hole has grown to a sufficiently large mass that its feedback (radiative and/or mechanical), despite the low gas heating efficiency, is able to suppress gas cooling. After that the system switches to a stable state corresponding to passively evolving ellipticals, when the accretion rate and radiative efficiency are very low, but the gas heating efficiency is high and energy input from the relativistic outflow keeps the gas hot.

Key words: galaxies: active - galaxies: jets - galaxies: nuclei

1 INTRODUCTION

It is now widely accepted that virtually every elliptical galaxy hosts a supermassive black hole (SMBH) at its center with its mass tightly correlated with the mass and stellar velocity dispersion of the galaxy itself (e.g. Ferrarese & Merritt 2000; Tremaine et al. 2002). During the early stages of galaxy evolution, when large quantities of cold gas are presumably present, these black holes accrete matter at high rates and are observed as bright QSOs once they have grown to a considerable mass. In contrast the central SMBHs of local elliptical galaxies usually have very small bolometric luminosities. Recent X-ray and radio observations suggest that, despite low observed luminosities, these SMBHs in local ellipticals eject material outflows that have a strong impact on the thermal state of the ambient hot gas, which is characterized by a relatively short cooling time and should cool and condense in the absence of an external source of energy. These outflows usually manifest themselves as bubbles of radio emitting plasma coincident with depressions in the X-ray images (e.g. Böhringer et al. 1993; Fabian et al. 2000; McNamara et al. 2000). The energetics of the outflows/bubbles and their evolution have been extensively discussed (e.g. Owen, Eilek & Kassim 2000; Churazov et al. 2001, 2002; Brüggen & Kaiser 2001; David et al. 2001; Nulsen et al. 2002; Fabian et al. 2003; Ruszkowski, Brüggen & Begelman 2004; Birzan et al. 2004). At least in several well studied objects the power of the outflow exceeds the observed bolometric luminosity and is sufficient to offset the gas cooling losses.

Radio emitting flows are also observed in X-ray binaries containing stellar mass black holes and the physics there is believed to be similar to that in SMBHs. For individual binaries the radio emission has been observed to vary depending on the X-ray flux and on the spectral state of the source (e.g. Fender & Belloni 2004). In particular it was found that an outflow ceases above a certain accretion rate (e.g. Fender et al. 1999). There are indications that active galactic nuclei (AGNs) may also exhibit a similar kind of radio power behavior (Maccarone, Gallo & Fender 2003). It thus seems reasonable to assume that the outflow behavior is similar for galactic binaries and SMBHs and consider the most straightforward implications for elliptical galaxies and their central SMBHs. This is the purpose of the present paper. Previously the role of feedback from growing SMBHs on their host galaxies has been discussed by many authors using different assumptions (e.g. Binney & Tabor 1995; Silk & Rees 1998; Ciotti & Ostriker 2001; Cavaliere, Lapi & Menci 2002; Wyithe & Loeb 2003; Granato et al. 2004; Murray, Quataert & Thompson 2005; Sazonov et al. 2005; Springel, Di Matteo & Hernquist 2005, Begelman & Nath, 2005).

2 BLACK HOLE ENERGY RELEASE IN X-RAY BINARIES AND AGNS

Simultaneous observations of several X-ray binaries, in particular black hole candidates, in radio and X-ray bands have recently led to the following broad picture (e.g. Gallo, Fender and Pooley 2003; Fender & Belloni 2004). In the so-called "low/hard" source state X-ray and radio fluxes are well correlated with a functional form $F_r \propto F_X^{0.7}$. In this state the accretion rate is low - $\dot{M} \ll \dot{M}_{\rm Edd}$, the accretion flow is optically thin (geometrically thick) and radiative efficiency (luminosity/$\dot{M}c^2$) is much lower than canonical 10%. Here $\dot{M}_{\rm Edd} = \frac{4\pi G m_p M_{BH}}{\eta c \sigma_T}$, $M_{\rm BH}$ is the black hole mass, G gravitational constant, m_p proton mass, c speed of light, σ_T Thomson cross section, and $\eta \approx$10%. For individual sources (a notable example is GX339-4) the F_r/F_X correlation extends over at least three orders of magnitude in X-ray luminosity. It can be extended by another 7-9 orders of magnitude by adding a large sample of individual AGNs (Maccarone et al 2003; Merloni, Heinz & Di Matteo 2003). In this state the kinetic power of radio emitting outflows can significantly exceed their radiative power both in AGNs and binaries (e.g. Owen et al. 2000; Gallo et al. 2003). The nucleus of M87 can be regarded as the prototypical example of an AGN in the low accretion rate mode. In M87, the energetics derived from the observed jets and radio lobes suggests an outflow power on the order of 10^{44} erg s^{-1}, requiring an accretion rate of order $3 \times 10^{-4} \dot{M}_{\rm Edd}$ onto a $3 \times 10^9 M_\odot$ black hole for an outflow efficiency (power/$\dot{M}c^2$) of 10%. On the other hand, the current X-ray luminosity of the nucleus is less than 10^{41} erg s^{-1} and even after bolometric correction it remains 10–100 times lower than the outflow power.

For binaries the F_r/F_X correlation breaks down when higher X-ray fluxes are considered (Fender et al. 1999; Gallo et al. 2003). This break is associated with the increased mass accretion rate and a transition of the source to the so-called "high/soft" state. In this state the bulk of the observed X-ray emission comes from a standard, optically thick and geometrically thin accretion disk (Shakura & Sunyaev 1973), and the spectra are reasonably well described by the multicolor black body model. In this state the radio emission drops by a large factor (or completely disappears) suggesting quenching of the outflow. Once again one can identify a similar behavior for AGNs (Maccarone, Gallo & Fender 2003), although the trend is less clear than for binaries.

There is, therefore, good observational evidence that the energy release via accretion onto black holes in X-ray binaries and AGNs depends on the accretion rate qualitatively as shown in Fig.1. At low rates there is a strong outflow whose power correlates with the accretion rate. The radiative efficiency at these rates is low, as e.g. in advection dominated flows (Esin, McClintock & Narayan 1997), so that the outflow dominates the output energetics. Numerous observations of Galactic X-ray binaries have shown that at an accretion rate of order of $\sim 10^{-2} - 10^{-1} \dot{M}_{\rm Edd}$ the sources make a spectral transition from the low/hard to high/soft state. We use this value as the characteristic accretion rate above which the outflow power decreases. In the particular case of GX339-4 the radio flux has dropped by a factor of more than 25 during the transition to the soft state (Fender et al. 1999), which can be viewed as evidence of a similarly strong decrease of the outflow power. In the absence of a justifiable quantitative model of the outflow we adopt a simple prescription (shown in Fig.1) according to which the outflow power drops by large a factor when the accretion rate rises from $\sim 10^{-2} \dot{M}_{\rm Edd}$ to $\sim \dot{M}_{\rm Edd}$.

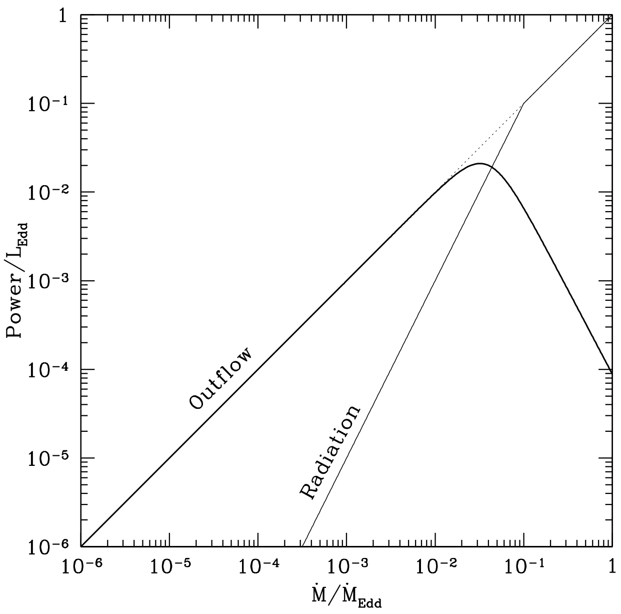

Figure 1. Sketch of black hole energy release as a function of mass accretion rate. At low accretion rates a significant fraction of accretion power goes into an outflow (thick solid line). Above a certain accretion rate, corresponding to the transition to the standard accretion disk mode, the outflow power decreases. The radiative power (thin solid line) is instead very low at low accretion rates and reaches a fixed fraction (∼10%) of $\dot{M}c^2$ at accretion rates above 0.01-0.1 of Eddington.

Despite the above justification of the picture presented in Fig.1, it may still be an oversimplification of the real situation. First, as is well known, ∼ 10% of QSOs exhibit strong radio emission (e.g. Ivezić et al. 2002), indicating that powerful outflows may sometimes be associated with rapidly accreting SMBHs. What determines the radio loudness/quietness of QSOs remains an open question. It is possible that apart from the instantaneous accretion rate, other properties such as black hole spin or the pre-history of the accretion rate may play crucial roles. An indication that the latter may indeed be important comes from observations in transient X-ray binaries of a short, intense radio outburst during the transition from low/hard to high/soft state – in the so-called very high state – when the accretion rate approaches the Eddington limit (Fender, Belloni & Gallo, 2004); such radio flares, however, have never been observed during the reverse transition (from high/soft to low/hard state). Importantly, it is not yet clear whether the observed radio outbursts are associated with a significant additional energy output or they mostly reflect a change in the emission properties of the previously (in the low/hard state) ejected material.

3 BLACK HOLE FEEDBACK IN ELLIPTICAL GALAXIES

We now discuss the conversion of energy released by accretion onto SMBHs into gas thermal energy in ellipticals.

At low accretion rates the most important form is mechanical energy input from outflows generated by the black hole. Examples of outflow interactions with the ISM are found in many elliptical galaxies (e.g. Finoguenov & Jones 2001). If the outflow is halted well within the region occupied by the cooling gas, then the efficiency of converting the outflow energy into the gas heating can be high, up to 100% (e.g. Churazov et al. 2002). For simplicity we assume that the gas heating rate due to SMBH feedback is equal to the outflow power. This leads to a dependence of gas heating rate on the accretion rate (Fig.2) that mirrors the outflow power curve (Fig.1).

Apart from the mechanical feedback, radiative gas heating, via photoionization and Compton scattering of radiation from the SMBH, should be at work (Ciotti & Ostriker 2001; Sazonov, Ostriker & Sunyaev 2004). Because of low efficiency of converting luminosity into heat the radiative feedback can be safely neglected at low accretion rates, but it can however be important at near-Eddington luminosities (see below). It may therefore contribute significantly (or dominate) the high-$\dot{M}$ part of the heating curve in Fig.2 far from its maximum. This insures that total feedback power (mechanical plus radiative) does not go zero near Eddington rate even if the outflow quenches completely.

It is convenient to characterize the gas heating power F through the efficiency δ of converting accreted mass into heat: $F = \delta c^2 \dot{M}$. For subsequent analysis we assume that at very low accretion rates (outflow regime), the efficiency is high, $\delta_O \approx const \sim 0.1$, while close to the Eddington limit, the efficiency is much lower, $\delta_E \ll \delta_O$.

The schematic heating curve plotted in Fig.2 predicts the maximum feedback power at the level of $0.02 \times L_{Edd}$, i.e. $\sim 2\ 10^{45}$erg/s for a $10^9 M_\odot$ black hole. Comparison with the most powerful outbursts identified so far in MS0735.6+741 (McNamara et al., 2005) and Hercules A (Nulsen et al., 2005), both having an estimated outburst power at the level of $\sim 2\ 10^{46}$erg/s, suggests that the maximum jet power can be an order of magnitude higher than adopted in Fig.2. Unless these are very exceptional systems or their power is significantly overestimated, the efficiency of energy extraction by jets might need to be upscaled significantly from $\sim 10\%$

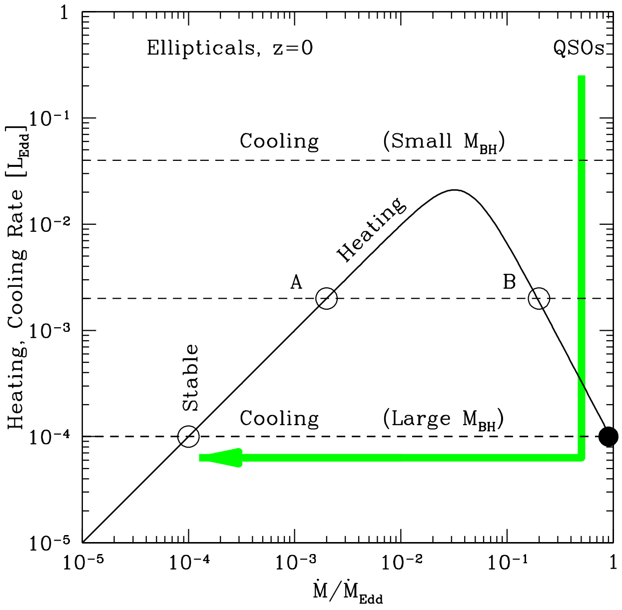

Figure 2. Illustration of gas heating and cooling in elliptical galaxies. The thick solid line shows, as a function of the SMBH accretion rate, the heating rate due to outflow, which is complemented/dominated by radiative heating near the Eddington limit. Horizontal dashed lines show the gas cooling rate. The upper cooling line represents a young galaxy in which a large amount of gas is present and/or the black hole is small. Feedback from the black hole is not able to compensate for gas cooling losses and the black hole is in the QSO stage with a near-critical accretion rate, high radiative efficiency and weak feedback. As the black hole grows it moves down in this plot. The black solid dot marks the termination of this stage, when the black hole is first able to offset gas cooling, despite the low gas heating efficiency. The lower cooling line illustrates present day ellipticals: a stable solution exists at low accretion rates when mechanical feedback from the black hole compensates gas cooling losses. The radiative efficiency of accretion is very low and black hole growth is very slow.

adopted here and/or the heating curve peaks at a higher accretion rate.

Consider now a gas halo feeding a black hole at its center. If the black hole has a mass such that its maximum possible heating power exceeds the gas losses (so that the cooling line intersects the heating curve in Fig.2, e.g middle horizontal dashed line), the system can find itself in one of two equilibrium states (labeled **A** and **B**), in which cooling is balanced by heating. We argue below that only one of these states is stable.

Consider for example that the mass accretion rate onto the black hole is described by the Bondi formula:

$$\dot{M}_{Bondi} = 4\pi\lambda (GM_{\rm BH})^2 c_s^{-3} \rho \propto s^{-3/2}, \tag{1}$$

where λ is a numerical coefficient that depends on the gas adiabatic index γ ($\lambda = 0.25$ for $\gamma = 5/3$), $c_s = \sqrt{\gamma \frac{kT_e}{\mu m_p}}$ is the gas sound speed, ρ is the gas mass density, and $s \propto T_e/\rho^{\gamma-1}$ is the gas entropy index. Then it is the gas entropy near the black hole which regulates the amount of heat supplied by the SMBH into the gas. Consider the system near state **B** (Fig.2), with a heating rate slightly exceeding cooling losses. The gas then heats up, its entropy increases, and it expands. The gas expansion will decrease the gas cooling losses. The Bondi accretion rate will also decrease. But according to our feedback prescription in the vicinity of **B** (see Fig.2) the feedback power will instead increase. Thus the imbalance between heating and cooling will increase and the system will evolve away from state **B**.

For the system in state **A** (Fig.2), the stability of the equilibrium depends on the specifics of energy deposition into the gas and on the gas distribution. We can verify the stability for a simple one-zone gas model. Consider a lump of gas with a fixed total mass M_{gas}, kept at fixed pressure. The total cooling losses of the lump $C \propto n^2R^3\Lambda(T) \propto n\Lambda(T)$, where n is the gas density, R the size of the lump, and $\Lambda(T)$ is the gas cooling function. If we neglect changes of the cooling function with temperature then $C \propto s^{-2/5}$. This is a less steep function of entropy than the feedback power $\propto \dot{M}_{Bondi} \propto s^{-3/2}$ near state **A** and therefore the equilibrium will be stable.

3.1 A Toy Model

We now consider the implications of our model for the evolution of elliptical galaxies. We completely neglect stellar feedback, which can be especially important for low mass systems. Thus the discussion below mainly refers to massive systems with velocity dispersions larger than ∼200 km/s.

We follow the picture of a quasi-steady cooling flow in an isothermal halo (e.g. White & Frenk 1991). We assume that the potential of the galaxy is described by an isothermal sphere $\phi = 2\sigma^2 \ln r$ and the initial gas distribution follows the dark matter:

$$\rho_{gas} = f_{gas}\frac{\sigma^2}{2\pi G r^2}, \quad (2)$$

where σ is the velocity dispersion, r is the distance from the center and f_{gas} is the gas mass fraction. The angular momentum of the gas is neglected. The initial mass of the black hole is assumed to be small enough that its feedback can be completely neglected (situation corresponding to the upper cooling line in Fig.2). The cooling radius $r_{\rm cool}$ is set by equality of the cooling time $t_{\rm cool} = \frac{3/2(n_e+n_i)kT}{n_e n_i \Lambda(T)} \approx \frac{3kT_e}{n_e\Lambda(T)}$ to the age of the system t, where n_e and n_i are the electron and ion densities:

$$r_{\rm cool} = \left(\frac{f_{gas}\Lambda(T)t}{3\pi m_p^2 G}\right)^{1/2} \approx 57\ t_9^{1/2}\Lambda_{23}^{1/2}\ {\rm kpc}, \quad (3)$$

where hereafter $\Lambda(T) = \Lambda_{23}\times 10^{-23}{\rm erg\ s^{-1}\ cm^{-3}}$, $\sigma = \sigma_{200}\times 200$ km/s, $t = t_9 \times 10^9$ yr and the gas fraction is set to $f_{gas} = 0.17$ (Cosmological baryon fraction). Inside the cooling radius the gas flows inward due to cooling losses, with the density of the gas increasing approximately as $r^{-3/2}$ and the temperature being approximately equal to the virial one ($T \approx 3\times10^6\sigma_{200}^2$ K). At a radius $r_s \ll r_{cool}$ (at least for massive systems) the cooling time becomes comparable to the sound crossing time of the region, $t_{\rm cool} \approx r_s/c_s$:

$$r_s = \frac{2}{9\sqrt{3}\pi^{3/2}}\frac{f_{gas}^{3/2}\Lambda(T)^{3/2}}{\gamma m_p^3 G^{3/2}\sigma^2 t^{1/2}} \approx 1.7\ \sigma_{200}^{-2}\ t_9^{-1/2}\ \Lambda_{23}^{3/2}{\rm kpc}. \quad (4)$$

In the vicinity of r_s the gas cools rapidly and the temperature drops. We assume that if a simple cooling flow solution extends down to r_s then cold gas will be present in large amounts in the system, stars will be actively forming, and the black hole will accrete at the Eddington rate, independently of the details. The black hole mass then grows exponentially with the Salpeter e-folding time $t_s \approx 4\times10^7$ yr: $M_{\rm BH} \propto e^{t/t_s}$. The mass cooling rate of the gas is instead a decreasing function of time:

$$\dot{M}_{\rm cool} = \frac{2}{\sqrt{3\pi}}\frac{f_{gas}^{3/2}\sigma^2\Lambda(T)^{1/2}}{m_p G^{3/2}t^{1/2}} \approx 180\ \sigma_{200}^2 t_9^{-1/2}\Lambda_{23}^{1/2}\ M_\odot/{\rm yr}. \quad (5)$$

White & Frenk (1991) noted that the gas infall rate, calculated as a time derivative of the gas mass within the virial radius ($r_{vir} = 2\sigma_{km/s}(1+z)^{-3/2}$ kpc), rather than the cooling rate may be a limiting factor. However for a redshift z of 2-3 the infall rate is not much smaller than the cooling rate (see Fig.2 of White & Frenk 1991). Therefore one should not expect dramatic changes if the cooling rate is replaced by the minimum of the infall and cooling rates, especially if massive systems are considered. We also note that at $z \sim$ 2-3 the cooling rate (Eq.5) is much larger than the Eddington accretion rate (for local M_{BH}/σ relation).

The gas cooling losses near r_s are accordingly $C \approx 3/2kT\frac{\dot{M}_{\rm cool}}{\mu m p} \propto t^{1/2}$. Additional losses between r_s and $r_{\rm cool}$ are of order of $C\ln(r_{\rm cool}/r_s)$. With time cooling losses will decrease relative to the (growing) heating power of the black hole accreting at the Eddington rate. With our definition of the feedback amplitude, the black hole accreting at the Eddington rate will be able to offset gas cooling provided that:

$$\delta_E c^2\dot{M}_{\rm Edd} \approx C \approx 3/2kT\frac{\dot{M}_{\rm cool}}{\mu m p}. \quad (6)$$

Substituting the expression for the Eddington accretion rate ($\propto M_{\rm BH}$) and solving for $M_{\rm BH}$ we find:

$$M_{\rm BH} \approx \frac{\eta}{\delta_E}\frac{\sigma^4 f_{gas}^{3/2}\Lambda(T)^{1/2}\sigma_T}{2\sqrt{3}\pi^{3/2}cG^{5/2}m_p^2 t^{1/2}} \approx \quad (7)$$
$$4\times10^8\left(\frac{\delta_E}{10^{-5}}\right)^{-1}\sigma_{200}^4 t_9^{-1/2}\Lambda_{23}^{1/2}\ M_\odot$$

for an accretion radiative efficiency $\eta = 0.1$. Once the black hole has grown to this size it will be able to prevent gas cooling, cold gas will disappear and star formation will cease. The entropy of the gas increases dramatically and the system evolves toward a low accretion rate solution. In this regime the accretion rate required to produce the same heating power as before is substantially sub-Eddington: $\dot{M} \sim \frac{\delta_O}{\delta_E}\dot{M}_{\rm Edd}$.

We can infer from equation (7) that for a black hole mass satisfying the observed $M_{\rm BH}$–σ relation (Tremaine et al. 2002), a balance between heating and cooling can be achieved for a quite low feedback efficiency (power/$\dot{M}c^2$) $\sim 10^{-5}$. The minimum possible feedback is provided by radiative heating, whose efficiency is $(10^{-3}$–$10^{-2})\tau$ (Sazonov et al. 2005), where τ is the optical depth of the heated gas. Using equations (2) and (4), we can estimate the optical depth of the cooling flow external to r_s as $\tau \approx 0.004\sigma_{200}^3\Lambda_{23}^{-1}$. Furthemore, for relatively large galaxies ($\sigma > 200$ km s^{-1}), the cooling flow extends to a few kpc from the SMBH, where gas can be heated on the time scale of SMBH growth (Sazonov et al. 2005). Therefore, radiative feedback alone appears sufficient to suppress the cooling flow once the black hole accreting at a near-critical rate reaches the observed $M_{\rm BH}$–σ relation. Any additional channel of energy input into the cooling gas, e.g. via relativistic jets, will only faciliate the establishment of thermal equilibrium.

The resulting system evolution is shown in Fig.2 as the gray track. The black hole first accretes at the Eddington level (vertical track) and then switches (horizontal track) to the low accretion rate mode. The vertical track corresponds to a very high radiation efficiency and active star formation (cold gas is continuously deposited), whereas in the low accretion regime the radiative efficiency is low and little star formation takes place in the galaxy.

Importantly, for the black hole mass for which the thermal equilibrium is reached, the maximum possible feedback power (maximum of the function F, see Fig.2) significantly exceeds the cooling losses of the gas. This has two possible implications. First, the transition to the low accretion rate state might be followed by a very large energy input from the SMBH and ejection of gas from the system. Present day ellipticals are rather gas poor and thus may have suffered significant gas loss during the transition phase. On the other hand, the large maximum feedback power ensures that the system will be able to find a stable equilibrium at a low accretion rate to support a large atmosphere of hot gas even without gas ejection. The latter case is probably relevant to cD galaxies in rich clusters. Since the gas heating efficiency in the low accretion rate state is high, the total mass accumulated by the SMBH over ~ 10 Gyr of passive evolution will not be significant: $M_{\rm BH} \approx 2\times 10^7 L_{43}\,(0.1/\delta_O)\,M_\odot$, where L_{43} is the gas cooling losses in units of 10^{43} erg s^{-1}. Only for rich clusters can the black hole significantly increase its mass in this mode (e.g. Fabian et al. 2002).

In rich clusters the cooling losses might exceed the maximum of the feedback curve. The central source can then enter a QSO mode again. The new episode of rapid accretion and black hole growth will continue until the SMBH grows enough to switch back to the low accretion rate mode. Such bursts of rapid accretion would be reminiscent of the models considered by Ciotti & Ostriker (2001). Similar episodes of QSO-type activity could be initiated by a merger with gas rich galaxies (as in simulations of Springel, Di Matteo, & Hernquist 2005) when large quantaties of cold/cool gas are suddenly dumped onto the existing black hole.

The above model assumes that when the gas is able to cool the SMBH is accreting at the Eddington rate. The results would be different if the accretion rate is set by the Bondi rate from the hot phase of a multiphase medium (along the line of reasoning suggested by Nulsen and Fabian 2000). The thermal instability within r_s, i.e. where the cooling time becomes shorter than the sound crossing time (e.g. Fall & Rees 1985) limits the density of the hot phase to maintain approximate equality of these time scales. As a result the Bondi accretion rate is limited to $\dot{M} \approx \phi \frac{kT}{\Lambda(T)} \eta c \sigma_T \dot{M}_{\rm Edd} \approx \phi\ 0.3\left(T/10^7\right)\Lambda_{23}^{-1}\dot{M}_{\rm Edd}$, where the dimensionless coefficient ϕ of order unity depends on the detailed assumptions (see Nulsen & Fabian 2000). For the most massive systems, this maximum accretion rate is not far from the Eddington rate, while for low masses, the maximum rate may be several orders of magnitude below Eddington.

4 SUMMARY

Guided by the analogy of SMBHs and the stellar mass black holes in X-ray binaries, we postulated a non-monotonic dependence of the SMBH feedback power on the mass accretion rate associated with a transition from geometrically thick accretion flow to a geometrically thin disk. The gas heating rate is maximal at substantially sub-Eddington accretion rates and drops strongly for near-Eddington rates. Such a scenario naturally leads to two stages in the evolution of a massive elliptical galaxy: i) QSO-like nucleus and active star formation at early epochs and ii) weak nucleus and passive evolution at the present time.

The main difference of the picture presented here with respect to previous work is that the phase of active black hole growth and star formation terminates when the SMBH produces enough power to substantially alter the thermal state of the infalling cooling gas, rather than to immediately expell the bulk of the gas from the galaxy, which requires much more energy (see e.g Silk & Rees 1998; Wyithe & Loeb 2003). In our picture, heating the gas increases its entropy and also enhances the SMBH feedback power. The gas can (and probably will) be expelled but this may happen over a long period of time after the end of the QSO stage. We showed that a $M_{\rm BH} \propto \sigma^4$ dependence with the observed normalization naturally arises for the simplest scenario of an isothermal gas halo if the SMBH feedback efficiency in the QSO phase is low ($\sim 10^{-5}$) and not varying significantly with black hole mass. Furthermore, the postulated non-monotonic feedback curve results in "over-grown" black holes, i.e. SMBHs capable of supporting much more massive atmospheres of hot gas than those present at the end of the QSO stage and afterwards.

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