A moderate cooling flow phase at galaxy formation

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ABSTRACT

I study the possibility that a cooling flow (CF) exists at the main phase of supermassive black hole (SMBH) growth during galaxy formation. To ensure that jets launched by the SMBH efficiently expel gas from the galaxy, as is required by recent results, the gas should be in the hot phase, rather than in cold clouds. The short radiative cooling time of the hot gas leads to the formation of a CF, but heating by the active galactic nucleus prevents catastrophic cooling. Cold blobs that start as instabilities in the hot phase feed the SMBH from an extended region, form an accretion disc, and lead to the formation of jets. These jets can expel large quantities of gas out of the galaxy. This cycle, which is termed the cold feedback mechanism in CFs in clusters of galaxies, might explain the correlation of SMBH to bulge masses. Stars are formed, but at a lower rate than what is expected when heating is not included. Such a CF is termed a moderate CF.

Key words: galaxies: bulges – galaxies: jets.

1 INTRODUCTION

The tight correlation between the supermassive black hole (SMBH) mass, \( M_{\text{BH}} \), and the velocity dispersion, \( \sigma \), of the hot component of the host galaxy (e.g. Gebhardt et al. 2000; Merritt & Ferrarese 2001; Gültekin et al. 2009) is well established, and so is the correlation between the SMBH mass and the bulge mass, \( M_{\text{bulge}} \) (e.g. Kormendy & Richstone 1995; Laor 2001). It is possible that the \( M_{\text{BH}}-M_{\text{bulge}} \) correlation is determined by a feedback process of the active galactic nucleus (AGN) of the host bulge, powered by the accreting SMBH. The feedback mechanism where AGN jets (outflow; wind) suppress gas from cooling to low temperatures and from forming stars was discussed for both cooling flows (CFs) in galaxies and clusters of galaxies (e.g. Binney & Tabor 1995; Nulsen & Fabian 2000; Reynolds, Heinz & Begelman 2002; Omma & Binney 2004; Soker & Pizzolato 2005), and in galaxy formation (e.g. Silk & Rees 1998; Fabian 1999; King 2003; Croton et al. 2006; Bower, McCarthy & Benson 2008; Shabala & Alexander 2009). By galaxy formation I will refer also to bulge formation in a spiral galaxy, and vice versa.

There are other attempts to explain this correlation. For example, in their model of bulge formation by coalescence of giant (\( M \sim 10^8 \text{M}_\odot \)) clumps, Elmegreen, Bournaud & Elmegreen (2008b) considered feedback by supernovae (SNe), but not by AGN activity. In their model, the SMBH at the centre of the galaxy is formed from the merger of the intermediate-mass black holes (BHs) that reside in each clump (Elmegreen, Bournaud & Elmegreen 2008a). The ratio of SMBH to bulge mass \( M_{\text{BH}}/M_{\text{bulge}} \sim 10^{-3} \) originates in the massive clumps. In the present paper I assume that the SMBH forms by accreting mass from the interstellar medium (ISM), and that the \( M_{\text{BH}}-M_{\text{bulge}} \) correlation is determined by an AGN feedback mechanism. It is determined in the sense that the AGN activity limits the ISM mass that is eventually converted to stars by expelling it out of the galaxy. The ejection of large quantities of gas out of the galaxy during its formation was found to be a necessary process in recent studies (e.g. Bower et al. 2008).

In a previous paper I tried to account for the SMBH–bulge masses correlation with a feedback mechanism based on jets launched by the SMBH. This feedback is based on narrow jets that are launched by the central SMBH, and expel large amounts of mass to large distances. The condition for an efficient expelling process is that the jets do not penetrate through the inflowing gas, such that they can deposit their energy in the inner region where the bulge is formed. A relation between the mass accreted by the SMBH and the mass that is not expelled, and is assumed to form the bulge, was derived (Soker 2009; this derivation is repeated in Section 4.3). It was noted that the same mechanism could operate in suppressing star formation in CF clusters, making a tight connection between the feedback in galaxy formation and CF clusters. In the present paper I extend the comparison between the feedback mechanism operating in CF clusters and during galaxy formation. My fundamental assumption is that the correlation between the SMBH mass and the host galaxy bulge mass is determined by an AGN feedback process that expel large quantities of gas out from the galaxy.

In Sections 2 and 3 I argue that for the feedback mechanism to be efficient, as required from my fundamental assumption, most of the gas should pass through the hot phase, unlike the case in the model studied by Binney (2004, 2005). In Section 4 I discuss a model where the feedback between the SMBH and star formation in the bulge occurs through a process similar to that operating in CFs in...
clusters of galaxies. A comparison of CF in clusters to the process at
galaxy formation was done in the past (e.g. Croton et al. 2006). In the
model discussed by Binney (2004, 2005), for example, heating by the
AGN activity and the ejection of large quantities of gas out from
the galaxy are crucial processes, as they are in the present model.
However, Binney (2004) proposed a model where the gas that forms
star has never been heated to the virial temperature, while that gas
that was heated to the virial temperature has negligible contribution
to star formation. In the model proposed in Section 4.2, on the other
hand, large quantities of gas in the hot phase cool to form stars.
The advantage in the presence of large amount of mass in the hot phase
is that the hot phase is more susceptible to AGN heating (Binney
2004; Cattaneo et al. 2006; Dekel & Birnboim 2006; Hopkins &
Elvis 2010). I summarize the proposed model in Section 5.

2 PROBLEMS WITH FEEDBACK DRIVEN
BY BONDI ACCRETION

I define the Bondi accretion radius by

\[ R_B = \frac{2GM_{BH}}{\mu c_s^2} = \frac{6}{5} \frac{GM_{BH} \mu mH}{kT}, \]

where \( M_{BH} \) is the SMBH mass, \( C_s = (5kT/3\mu mH)^{1/2} \) is the ISM
sound speed and all other symbols have their usual meaning. The
Bondi accretion rate for an adiabatic index of \( \gamma = 5/3 \) is (Bondi
1952)

\[ \dot{M}_{Bondi} = 0.25\pi R_B^2 \rho C_s, \]

where \( \rho \) is the density at a large distance from the accreting body.
The characteristic inflow time is

\[ \tau_{\text{flow}} \equiv \frac{R_B}{C_s}. \]

(The inflow velocity at \( R_B \) is \( \ll C_s \), and the practical inflow timescale is longer than \( \tau_{\text{flow}} \).)

A condition for the existence of a Bondi-type accretion flow is that the radiative cooling time is longer than the inflow time \( \tau_{\text{cool}} > \tau_{\text{flow}} \). Otherwise the ISM rapidly cools, the value of \( C_s \) rapidly decreases, and the assumptions that lead to the Bondi accretion flow in a hot ISM break down. Namely, we are in the regime of accreting cold gas, the problems of which are discussed in Section 3. This condition reads

\[ \frac{3}{2} \frac{n_kT}{\Lambda} > \frac{R_B}{C_s}, \]

where \( n_e, n_p \) and \( n_H \) are the total, electron and proton number density, respectively. Condition (4) can be cast in the form

\[ 5.2 \frac{\mu m_H kT}{\Lambda} R_B C_s^2 > 0.25\pi R_B^2 \rho C_s. \]

For the cooling function \( \Lambda \) assume a zero metallicity composition and take the temperature range \( T \geq 10^7 \) K. This gives \( \Lambda_0(T) \simeq 2 \times 10^{-23} (T/10^K)^{1/2} \text{ erg cm}^3 \text{s}^{-1} \) (Sutherland & Dopita 1993). For lower temperatures and higher metallicities the conclusions will be stronger even, as cooling time is shorter. Substituting equation (5) into equation (2) with the above approximation for \( \Lambda \), gives

\[ M_{Bondi} < 1.6 \times 10^{-10} \left( \frac{T}{10^7 \text{ K}} \right)^{1/2} \frac{M_{BH}}{M_{\odot}} \frac{M_{\odot}}{\text{ yr}^{-1}}. \]

The actual limit is lower even for three reasons. (1) Some fraction of metals will be present, increasing the cooling rate. (2) The inflow time should be shorter than the cooling time not only from the Bondi radius but also from a distance of several Bondi radii. (3) In galaxies that do not sit at the centre of groups and clusters, the virial temperature of the gas is \( < 10^7 \) K. For a temperature of \( T = 2 \times 10^6 \) K and zero metallicity, the cooling function is lower by a factor of 1.6, and the cooling time shorter by a factor of 5/1.6 = 3. The numerical coefficient in equation (6) is \( \sim 5 \times 10^{-10} \text{ M}_{\odot}^{-1} \text{ yr}^{-1} \).

We can compare the limit from the Bondi accretion as given in equation (6) with the Eddington limit

\[ M_{\text{Edd}} = 2.5 \times 10^{-8} \left( \frac{\epsilon}{0.1} \right)^{-1} \frac{M_{BH}}{M_{\odot}} \frac{M_{\odot}}{\text{ yr}^{-1}}, \]

where \( \epsilon \) is the efficiency of converting mass to radiation in the accretion process. We find that \( M_{Bondi} < 0.1 \text{ M}_{\text{Edd}} \). It seems there is no time for the BH to grow if it is limited by the Bondi accretion, as the e-folding time is

\[ \tau_{\text{f}} = M_{\text{BH}} \frac{M_{Bondi}}{M_{\text{BH}}} > 6 \times 10^8 \left( \frac{T}{10^7 \text{ K}} \right)^{-1/2} \text{ yr}. \]

To grow by a factor of 1000, the minimum time required is \( \sim 4 \) Gyr, with a more likely value of \( > 5 \) Gyr. Clearly, this process cannot explain the rapid growth of SMBH during galaxy formation.

There are two possible solutions to the feeding problem.

(1) Most of the ISM mass is in a cold \( T \lesssim 10^7 \) K \( \ll T_{\text{virial}} \) phase, for which the Bondi accretion radius is much higher. The problem with cold clouds is that they are very dense. It is very hard to remove such clouds from the galaxy. Moreover, cold clouds are more likely to form stars. This solution makes it very hard to explain the termination of star formation. This is the subject of the next section. In any case, models that include Bondi accretion consider the hot \( T \gtrsim 10^7 \) K phase.

(2) Most of the mass is in the hot phase with \( T \approx T_{\text{virial}} \). However, the SMBH is feed by cold clumps that are embedded in the hot ISM. The clumps as a group contain a small fraction of the total ISM mass. This solution to maintain feedback heating in cluster CFs is termed the cold feedback mechanism (Pizzolato & Soker 2005, 2010; Soker 2006, 2008b). In Section 4 I compare this mechanism as it operates in galaxy formation at high redshifts to its role in low-redshift cluster CFs.

3 PROBLEMS IN MAINTAINING FEEDBACK
WITH MASSIVE COLD ISM

It is possible that most of the ISM mass resides in cold (\( \sim 10^4 \) K) clouds, rather than being close to the virial temperature and in a hydrostatic equilibrium. The problem in this case is that the AGN feedback efficiency is too low, because it is extremely difficult to expel dense clouds from the inner regions of the galaxy. In a recent attempt Hopkins & Elvis (2010) note that AGN feedback works more efficiently on the hot phase, and consider a chain of processes to overcome this problem. In their model the clouds contain \( \sim 90 \) per cent of the mass, while \( \sim 10 \) per cent of the ISM mass is in the hot phase at hydrostatic equilibrium. A shock propagating through the hot phase causes the clouds to expand, such that radiation pressure from the AGN is more efficient in expelling the bloated clouds. Even in this more efficient scenario, the mass expelled in their model is not sufficient for the feedback mechanism studied here. Hopkins & Elvis (2010) take the bulge mass to be \( 10^{11} \) M\(_{\odot}\), while the ISM mass is only \( 10^{10} \) M\(_{\odot}\). After a time of \( t = 10^8 \) yr from the start of their calculation, the mass expelled in their model is \( \Delta M_e = 5 \times 10^9 \) M\(_{\odot}\). During the same period, for an efficiency of 10 per cent, the SMBH mass has grown by \( \Delta M_{\text{SMBH}} \approx 10^8 \) M\(_{\odot}\). This ratio of \( \Delta M_e / \Delta M_{\text{SMBH}} \approx 50 \) is lower by more than an order of magnitude

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from the one required in feedback models that account for the bulge to SMBH masses ratio, if the feedback is to determine the final mass of the bulge. Had they include radiative cooling, the efficiency of expelling the ISM would be lower even.

The conclusion is that for an AGN feedback to work, most of the gas in the inner regions, \( r \lesssim 10 \) kpc \( \sim 0.1 R_* \), must reside in the hot phase; \( R_* \) is the virial radius.

Although the AGN feedback requires the inner regions to be mostly in the hot phase, the gas feeding the galaxy at larger regions can be cold. In the cosmological cold streams model (Dekel et al. 2009a,b and references therein) three cold, low entropy, streams of gas penetrate the virial radius without being shocked, and reach the central region. Shocks near the centre are not resolved in the numerical simulations presented by Dekel et al. (2009a), as their resolution is 1.4 kpc. Eventually, the streams must encounter a shock wave near the centre. The typical influx rate considered by Dekel et al. (2009a) is \( \dot{m} \sim 30 M_\odot \) yr\(^{-1}\) rad\(^{-2}\). At a distance \( r \) from the centre the post-shock total (protons, electrons and nuclei) number density is

\[
n \simeq 1 \left( \frac{\dot{m}}{30 M_\odot \text{yr}^{-1}\text{rad}^{-2}} \right) \left( \frac{v}{300 \text{km s}^{-1}} \right)^{-1} \left( \frac{r}{5 \text{kpc}} \right)^{-2} \text{cm}^{-3},
\]

where \( v \) is the pre-shock inflow velocity, scaled with the inflow velocity at \( r \sim 5 - 10 \) kpc from the centre, according to Dekel et al. (2009a). The post-shock temperature is \( \sim 10^6 \) K.

For a temperature of \( \sim 10^8 \) K, and zero metallicity, the cooling function is \( \Lambda_0 \simeq 10^{-23} \text{erg cm}^{-3} \text{s}^{-1} \) (Sutherland & Dopita 1993). The cooling time of the post-shock gas is

\[
\tau_{cs} \simeq 3 \times 10^6 \left( \frac{\dot{m}}{30 M_\odot \text{yr}^{-1}\text{rad}^{-2}} \right)^{-1} \left( \frac{v}{300 \text{km s}^{-1}} \right)^{3/2} \times \left( \frac{r}{5 \text{kpc}} \right)^{-2} \left( \frac{\Lambda_0}{10^{-23} \text{erg cm}^{-3} \text{s}^{-1}} \right) \text{yr},
\]

where the dependence of the post-shock temperature on velocity has been used. The half opening angle of a stream is \( \sim 10^{-15}; 1 \) scale with 12.5. The pressure of the post-shock gas is larger than that of its surroundings, and it expands to the sides in a typical time of

\[
\tau_f \simeq \frac{r \sin 12.5}{v} = 3.5 \times 10^6 \left( \frac{v}{300 \text{km s}^{-1}} \right)^{-1} \left( \frac{r}{5 \text{kpc}} \right) \text{yr}.
\]

At \( r \sim 5 \) kpc the radiative cooling time is about equal to the expansion time of the post-shock region \( \tau_{cs} \simeq \tau_f \). Heating by the AGN will make the formation of a shock wave more likely. Cantalupo (2010) showed that ionization by star-forming regions can remove cooling agents (ions) from the gas and by that efficiently reduces radiative cooling and transforms a cold mode accretion into a hot one. The effect is larger even when radiation from the AGN is considered. The effect of removing cooling ions comes in addition to the heating discussed next. Let the gas mass in the inner region be equal to the stellar mass \( \sim 10^{11} M_\odot \). With a total number density of \( n \simeq 1 \text{cm}^{-3} \) the mass resides within a radius of \( \sim 10 \) kpc. To maintain this mass that has a radiative cooling time of \( \sim 3 \times 10^6 \) yr at a temperature of \( T \sim 10^6 \) K, requires a heating power of \( E_H \simeq 4 \times 10^{44} \text{erg s}^{-1} \). With an efficiency of 10 per cent in converting mass to energy, the accretion rate on to the SMBH is \( \sim 0.1 M_\odot \) yr\(^{-1}\). In \( 10^7 \) yr the SMBH gains a mass of \( \sim 10^6 M_\odot \). In reality, the amount of ISM mass will be lower, as part of it is continuously forming stars, while some of the incoming gas is expelled back to large distances. This crude calculation and the reduction in radiative cooling rate as discussed by Cantalupo (2010) show that heating by the AGN can maintain a shock wave at a radius of \( r \gtrsim 5 \) kpc.

There is no problem in the scenario proposed here that the streams penetrate the virial radius, at \( R_* \sim 50 - 100 \) kpc, as in the simulations presented by Dekel et al. (2009a). However, the model here does require that the streams eventually are shocked at \( r \gtrsim 0.1 R_* \), and a hot pseudo-static atmosphere is formed. The presence of hot static atmosphere around an already grown SMBH was assumed before, e.g. Short & Thomas (2009).

4 A COOLING FLOW PHASE

4.1 The cold feedback mechanism in low-redshift clusters

In the cold feedback model for clusters of galaxies (Pizzolato & Soker 2005; Pizzolato & Soker 2010; Soker 2006, 2008a) mass accreted by the central SMBH originates in non-linear overdense blobs of gas residing in an extended region of \( r \sim 5 - 50 \) kpc; these blobs are originally hot, but then cool faster than their environment and sink toward the centre (see also Revaz, Combes & Salome 2008). The mass accretion rate by the central BH is determined by the cooling time of the intracluster medium (ICM), the entropy profile, and the presence of inhomogeneities (Soker 2006). Most important, the ICM entropy profile must be shallow for the blobs to reach the centre as cold blobs. Wilman, Edge & Swinbank (2009) suggest that the behaviour and properties of the cold clumps they observe in the cluster A1664 support the cold feedback mechanism.

The cold feedback mechanism in clusters has the following consequences.

(1) CFs do exist, but at moderate mass cooling rates: the moderate CF model (Soker et al. 2001). Indeed, in many CF clusters the heating cannot completely offset cooling (e.g. Clarke, Blanton & Sarazin 2004; Hicks & Mushotzky 2005; Bregman et al. 2006; Salome et al. 2008; Hudson et al. 2010) and some gas cools to low temperatures and flows inward (e.g. Peterson & Fabian 2006) and forms stars (McNamara, Wise & Murray 2004; Wise, McNamara & Murray 2004). Star formation is prominent when the radiative cooling time of the hot gas is short (Rafferty, McNamara & Nulsen 2008). These observations suggest that indeed cooling of gas from the hot phase to low temperatures does take place, including star formation. It is important to note that star formation and the feeding of the SMBH occur simultaneously.

(2) The cold feedback mechanism explains why real clusters depart from an ‘ideal’ feedback loop that is 100 per cent efficient in suppressing cooling and star formation. Simply, the feedback requires that non-negligible quantities of mass cool to low temperatures. Part of the mass falls to small radii. Part of this mass forms star, another part is ejected back, and a small fraction is accreted by the central SMBH.

(3) Part (likely most) of the inflowing cold gas is ejected back from the very inner region. This is done by the original jets blown by the SMBH (Soker 2008b). The ejection of this gas is done in a slow massive wide (SMW) bipolar outflow, which are actually two jets. The basic mechanism is that the jet does not puncture a hole in the ICM, but rather deposits its energy in the inner region. Wide enough jets deposit their energy in the inner regions rather than puncturing a hole and expanding to large distances. Rapidly precessing jets or a relative motion of the medium also prevent such a puncturing. In the case of the formation of low-density bubbles in the ICM, it has been shown that in addition to SMW
4.2 A moderate cooling flow phase at galaxy formation

In their study of galaxy formation with AGN feedback, Croton et al. (2006) consider the formation of an extended (up to the virial radius of the dark halo) hot atmosphere, and that gas from the central region of this atmosphere might be accreted on to a central object through a CF. In this section I take upon this, and consider the moderate CF model with a cold feedback. Namely, the gas that feeds the SMBH originates in an extended region as cooling blobs, and not as a Bondi-type accretion. Heating of the inner regions by the AGN is a significant process, and the AGN activity level is regulated by the accretion of cold blobs from an extended region.

I differ from Croton et al. (2006) in a crucial manner. In their model the main growth of the SMBH occurs in the ‘quasar mode’ at high redshifts (z > 2). During the CF phase of Croton et al. (2006) the accretion rate is low, and the mass of the SMBH does not increase by much. As shown in Section 4.3, in the present model, the correlation between the SMBH mass and the bulge mass is set by a feedback process. For the feedback process to be efficient, I require the presence of a CF. Therefore, in the present model the CF appears much earlier than in the model discussed by Croton et al. (2006). The redshift at which the moderate CF operates to form stars and feed the SMBH is determined by the specific model of galaxy growth that one uses. I do not argue for a different global feeding of gas to the galaxy, and therefore the SMBH growth period, as well as that of the bulge, is as in the specific model, e.g. at z > 2 in the model of Croton et al. (2006), and in the redshift range of 1–5 in the model of Bower et al. (2006, 2008). I limit myself to claim that a CF phase takes place during the main growth phase. The proposed process can be incorporated in large-scale simulations as subgrid physics. Namely, when mass is flowing to feed the central region, for both star formation and SMBH growth, one can use the proposed mechanism to operate the feedback process (as the inner region is not resolved by the large-scale simulations).

I start when the SMBH mass is already ~0.1–10 per cent of its final mass, and the bulge/galaxy is already in the formation process. However, most of the stars in the bulge (or elliptical galaxy) have yet to be formed, and so does the SMBH mass. Cold streams that feed the galaxy (Dekel et al. 2009a; Dekel, Sari & Ceverino 2009b) are assumed to be shocked at r > 10 kpc, such that most of the mass resides in the hot phase. The cooling time of the hot phase is short, and thermal instabilities lead to the formation of cool blobs that fall inward. These cold blobs are not much cooler than their surroundings and can be expelled relatively efficiently by the jets launched by the AGN when AGN activity is high (see Section 4.3). A fraction of these blobs feed the SMBH. Heating by the SMBH activity, mainly by jets, facilitates the formation of this structure. The jets launched by the accreting SMBH only heat the gas, but as is the case in the cold feedback mechanism (Pizzolato & Soker 2005), the jets accelerate large quantities of gas outward. A structure similar to that in cluster CF at low redshifts has been formed. Table 1 compares the properties of the two types of the moderate CF models.

There are, however, two prominent qualitative differences between the proposed CF model at galaxy formation and that in CF in clusters of galaxies.

1. In the case of galaxy formation the cooling time in the inner ~1 kpc is shorter than the inflow time (Section 2). The gas cools very rapidly, pressure support is lost and an inward supersonic flow is formed (Soker & Sarazin 1988). In clusters, on the other hand, the cooling time is longer than the dynamical time at all radii, and no such flow is formed; the gas feeding the SMBH is cold, but it originates in the hot phase. Some discussion of this feeding mode is given by Croton et al. (2006). In addition to this supersonic flow, cold blobs formed from the hot phase at larger radii feed the SMBH as well, as in the cold feedback model for heating CF in clusters (Pizzolato & Soker 2005, 2010; Soker 2006, 2008a).

2. In clusters, the region where cooling takes place is ~10–50 kpc, or about a fraction ~0.1–0.3 of the cooling radius. Most of the ICM mass resides outside this radius. Any AGN activity can move mass from inner regions to regions further out, but the huge amount of mass in the outer regions prevents the mass to flow to very large distances from the centre. The situation is different in the proposed CF model at galaxy formation, where most of the mass reside in regions having a cooling time shorter than the age of the system. The CF is a major process. Still, the heating by the central AGN ensures the presence of a hot phase, and prolongs the time it takes the gas to cool. That most of the mass is residing in the hot phase ensures an efficient coupling of jets launched by the AGN to the ISM. This coupling will be particularly efficient when the mass inflow rate is >10^4 times the accretion to the SMBH, a ratio that might account for the SMBH–bulge masses correlation (Soker 2009; Section 4.3 below).

It is interesting to compare the model proposed here with that discussed by Binney (2004). In both models heating, aided by reduction in radiative cooling rate (Cantalupo 2010), by the AGN activity is crucial, and in both models the ejection of large quantities of gas out from the galaxy takes place. The main difference is that Binney (2004) attributes all star formation to gas that was never heated to about the virial temperature. Instead, I suggest that a large fraction of the gas is shocked to the virial temperature, and is further heated by the AGN to prolong its hot phase. Most of the gas stays in the hot phase for a time longer than the dynamical time, and forms
a (pseudo) static medium. Large quantities of this gas later cool, and form stars, as observed in cluster CF (but at lower efficiency). As the hot gas is much more susceptible to AGN activity, it allows for a feedback process from the AGN to work, and determine the masses ratio of the SMBH and bulge (Soker 2009).

### 4.3 Correlation of SMBH–bulge masses

In this section I briefly summarize the derivation of the correlation between the SMBH mass and the host galaxy bulge mass (Soker 2009). I will not repeat all steps and will not explain all assumptions, as they are in that paper. I will, however, make some modifications to account for the present proposal of a CF phase at galaxy formation, and to incorporate the new results of Soker & Merion (2010).

The basic assumptions are as follows.

1. The feedback mechanism is driven by jets.
2. The properties of jets launched by SMBH have some universal properties. As is shown in a new paper (Soker & Merion 2010), the basic property is the ratio of the total momentum discharge in the jets to the quantity $M_{\text{acc}} c$; $\epsilon_p = M_{\text{j}} v_{\text{j}} / (M_{\text{acc}} c)$, where $M_{\text{acc}}$ is the accretion rate on to the SMBH, $M_{\text{j}}$ is the mass flow rate into the two jets and $v_{\text{j}}$ is the jets’ speed. Soker & Merion (2010) find from statistical analysis of 10s of galaxies that in the feedback model for the correlation $\epsilon_p = 0.038 \pm 0.06$.

3. The mass flowing in at early stages, i.e. the mass available for star formation, is very large. Namely, the mass that is converted to stars is limited by the feedback mechanism and not by the mass available in the SMBH surroundings. This is supported by studies of galaxy formation (e.g. Bower et al. 2008).

4. There is a relative transverse (not to be confused with the radial inward velocity) motion between the SMBH and the inflowing mass of $v_{\text{rel}} \simeq \sigma$.

5. The cooling surrounding mass $M_{\text{c}}$, that resides at a typical distance $r_c$ and having a density $\rho_c$ (see below) is flowing inward at a velocity of $\sim \sigma$. Thus, $M_{\text{c}} \simeq 4\pi r_c^2 \rho_c$, and it is resupplied on a time-scale of $\sim r_c / \sigma$. This mass will mainly form stars if it is not expelled by the jets. This assumption is in the heart of the proposed CF phase at galaxy formation. Namely, that the inflowing gas, be it a CF that reaches a fast speed at $r \sim 1$ kpc (where the cooling time is short) or composed of cool clumps, is vulnerable to the jets launched by the central SMBH. The inflowing gas or clumps are cooler than the virial temperature but not by much, hence their density is not much lower than that of the surrounding hot gas. They are not the very dense clumps at low temperatures that were discussed in Section 3, and they can be expelled by the jets.

We note that $M_{\text{c}} \gg M_{\text{acc}}$, as only a small fraction of the inflowing gas at scales of $\sim 0.1$–10 kpc is accreted by the SMBH.

### Table 1. Comparing moderate CF models.

| Property | Low-c clusters | Galaxy formation |
|----------|----------------|------------------|
| Central e⁻ density ($n_{\text{e}}$) | 0.1 cm⁻³ | 10 cm⁻³ |
| Central temperature ($T_{\text{c}}$) | 3 × 10$^7$ K | 10⁶ K |
| System age ($t_{\text{age}}$) | 10¹² yr | 10⁵ yr |
| Central cooling time (t_{\text{c}}) | 5 × 10⁶ yr | 10² yr |
| Cooling radius ($r_{\text{c}}$) | 100 kpc | 30 kpc |
| Dynamical time at $0.01r_{\text{c}}$ ($t_{\text{d1}}$) | 10⁶ yr | 5 × 10⁵ yr |
| $\tau_{\text{c}}/\tau_{\text{d1}}$ | 0.1 | |
| Raw cooling rate ($\dot{M}_{\text{c}}$) | 10⁻¹³ M$_\odot$ yr⁻¹ | 10⁻¹⁰ M$_\odot$ yr⁻¹ |
| Star formation rate ($\dot{M}_{\text{s}}$) | 0–0.1 $\dot{M}_{\text{j}}$ | ~0.1–0.5 $\dot{M}_{\text{j}}$ |
| Source of gas feeding the SMBH | Cold blobs from an extended region | Cold blobs from an extended region + inner supersonic inflow |
| Fate of most gas expelled from the inner region | Inflating large low-density bubbles | (a) Depart from 100 per cent efficiency in supressing star formation |
| | | (b) Shallow entropy profile |
| | | (c) Massive outflows that can inflate ‘fat bubbles’ |
| | | (d) Can operate without the need for failed Bondi accretion (Section 2) |
| Results and implications of the cold feedback mechanism | | (a) Most of the ISM is susceptible to SMBH jets |
| | | (b) Expelling huge amounts of mass from the galaxy |
| | | (c) Can account for the $M_{\text{BH}}$–$M_{\text{bulge}}$ correlation (Soker 2009; Section 4.3) |
| | | (d) Can operate without the need for failed Bondi accretion |

*a* In the moderate CF model heating is important, but cooling of gas to low temperatures does occur, although at a much lower rate than that expected if no heating exists.

*b* The values are crude, and most are given to an order of magnitude.

*c* Some of the time-scales are calculated by using equations from Section 2.

*d* The cooling time in galaxy formation is lower even, as a zero metallicity was assumed here, but some metals will be present at an age of $\sim 10^5$ yr.

*e* The cooling radius $r_{\text{c}}$ is the radius at which the radiative cooling time (no heating included) equals the age of the system.

*f* Raw cooling rate is the mass cooling rate if no heating was present.
If the jets penetrate through the surrounding gas they will be collimated by that gas, and two narrow collimated fast jets will be formed, similar to the flow structure in the simulations of Sutherland & Bicknell (2007). By fast it is understood that the jet’s velocity is not much below its original velocity. If, on the other hand, the jets cannot penetrate the surrounding gas they will accelerate the surrounding gas and form SMW outflow (Soker 2008b).

I now derive (Soker 2009) the conditions for the jets not to penetrate the surrounding gas, but rather form a SMW outflow. Let the jets from the inner disc zone have a mass outflow rate in both directions of $M_\text{f}$, a velocity $v_\text{f}$, and let the two jets cover a solid angle of $4\pi\delta$ (on both sides of the disc together). The density of the outflow at radius $r$ is

$$\rho_\text{f} = \frac{M_\text{f}}{4\pi r^2 v_\text{f}^2}. \quad (12)$$

Let the jets encounter the surrounding gas residing within a distance $r_\text{s}$ and having a typical density $\rho_\text{s}$; this is the inflowing cooling gas, that if it is not expelled will form stars. The head of each jet proceeds at a speed $v_\text{h}$ given by the balance of pressures on its two sides. Assuming supersonic motion this equality reads $\rho_\text{f} v_\text{h}^2 = \rho_\text{s}(v_\text{h} - v_\text{s})^2$, which can be solved for $v_\text{h}$:

$$\frac{v_\text{h}}{v_\text{h}} - 1 = \left(\frac{4\pi\delta^2 v_\text{f}\rho_\text{s}}{M_\text{f}}\right)^{1/2} \left(\frac{\delta M_\text{f} v_\text{f}}{M_\text{s} \sigma}\right)^{1/2} = 1225 \left(\frac{M_\text{f}}{10^5 M_\odot}\right)^{1/2} \left(\frac{\delta}{0.1}\right)^{1/2} \left(\frac{v_\text{f}}{c}\right)^{1/2} \left(\frac{\sigma}{200 \text{ km s}^{-1}}\right)^{-1/2}, \quad (13)$$

where in the second equality the mass inflow rate $M_\text{s} \approx 4\pi\rho_\text{s} \sigma^2$ (by assumption 5) has been substituted. The time required for the jets to cross the surrounding gas and break out of it is given by

$$t_\text{p} \simeq \frac{r_\text{s}}{v_\text{h}} \simeq \frac{r_\text{s}}{v_\text{f}} \left(\frac{\delta M_\text{f} v_\text{f}}{M_\text{s} \sigma}\right)^{1/2} = 4 \times 10^6 \left(\frac{r_\text{s}}{1 \text{ kpc}}\right) \text{ yr}, \quad (14)$$

where in the last equality the same values as in equation (13) have been used.

If there are no changes in the relative geometry of the SMBH and inflowing mass, the jets will rapidly penetrate the surrounding gas and expand to large distances. In this case the jets will not deposit their energy in the inflowing gas. For an efficient deposition of energy to the inflowing gas, we require that there will be a relative transverse (azimuthal) motion between the SMBH and the inflowing gas, such that the jets continuously encounter fresh mass. The relevant time is the time that the transverse motion of the jet crosses it width $r_\text{f} \equiv D_\text{j}/v_\text{rel} \simeq D_\text{j}/\sigma$, as by our assumption 4 the relative velocity is $v_\text{rel} \simeq \sigma$. The width of the jet at a distance $r_\text{s}$ from its source is $D_\text{j} = 2r_\text{s} \sin \alpha$, where $\sigma$ is the half opening angle of the jet. For a narrow jet sin $\alpha \simeq \alpha \simeq (2\delta)^{1/2}$, and

$$\tau_\text{s} = \frac{2(2\delta)^{1/2}}{v_\text{rel}} = 4.4 \times 10^9 \left(\frac{r_\text{s}}{1 \text{ kpc}}\right) \left(\frac{v_\text{rel}}{200 \text{ km s}^{-1}}\right)^{-1} \left(\frac{\delta}{0.1}\right) \text{ yr}. \quad (15)$$

The demand for efficient energy deposition, $\tau_\text{s} \lesssim t_\text{p}$, reads then

$$\frac{M_\text{s}}{M_\text{f}} \gtrsim \frac{8 \pi \rho_\text{s} \sigma^2}{v_\text{rel}^2}. \quad (16)$$

This result can be understood as follows. The ratio $v_\text{f}/\sigma/v_\text{rel}$ comes from the ratio of the ram pressure of the narrow jet to that of the ambient gas which disturbs the jet, and from the relative transverse motion of the jet and the ambient gas. The number 8 comes from the geometry of a narrow jet with a relative transverse velocity to that of the ambient gas. Using the definition $\epsilon_\text{p} \equiv M_\text{f} v_\text{f}/(M_\text{acc} c)$ from assumption 2, we derive

$$\frac{M_\text{s}}{M_\text{acc}} \gtrsim 8 \epsilon_\text{p} \frac{\sigma^2}{v_\text{rel}^2} = 480 \left(\frac{\epsilon_\text{p}}{0.04}\right) \left(\frac{\sigma}{200 \text{ km s}^{-1}}\right)^{-1} \left(\frac{\sigma}{v_\text{rel}}\right)^{-2}. \quad (17)$$

Again, it is expected that in its formation phase the galaxy will not be fully relaxed, and that the relative transverse velocity of the AGN and the inflowing gas will be of the order of the stellar dispersion velocity, i.e. $v_\text{rel} \simeq \sigma$.

The accretion rate $M_\text{acc}$ is the accretion rate on to the SMBH, and the inflow rate of the surrounding gas is assumed to form stars in the bulge (if it is not expelled by the jets). If the inflow rate is above the value given by equation (17), the deposition of energy by the jets is efficient enough to expel the mass back to large distances and heat it (Soker 2008b). The interaction of the (narrow or wide) jets blown by the SMBH with the inflowing gas will form a wide outflow (SMW jets), that will expel more of the hot gas that is vulnerable to the jets. Namely, the jets blown by the SMBH will not allow the bulge to form stars at a rate larger than the value of $M_\text{s}$, given by equation (17). Following Soker (2009) then, the SMBH to bulge mass ratio is equal to $M_\text{acc}/M_\text{s}$. Equation (17) yields $M_\text{BH} \simeq 0.002 M_\text{bulge} \left(\frac{\epsilon_\text{p}}{0.04}\right)^{-1} \left(\frac{\sigma}{200 \text{ km s}^{-1}}\right)^{-1} \left(\frac{\sigma}{v_\text{rel}}\right)^{-2}$.\hspace{1cm} (18)

The last equation closes the feedback cycle, in showing that a correlation can be driven by jets blown by the SMBH into the hot ISM. A key issue is that the medium is in the hot phase such that its density is not too high, and therefore it is vulnerable to the action of the jets. This hot phase feeds the SMBH via the process of a moderate CF.

5 SUMMARY

Results from recent years show that the process of galaxy formation requires non-gravitational energy source not only to heat the gas but also to expel large quantities of gas out from the galaxy (Bower et al. 2008). To efficiently eject the ISM from the galaxy by AGN activity the gas must be in the hot phase, namely, its temperature must be about the virial temperature (e.g. Hopkins & Elvis 2010). The conclusion from these studies is that most of the ISM during galaxy formation must evolves through the hot phase. This gas has a short cooling time, and a CF is formed in the still-forming galaxy.

In the present paper I assumed that the $M_{\text{BH}}–M_{\text{bulge}}$ correlation is determined by an AGN feedback mechanism that operates during a CF phase at galaxy formation (Section 4.3). It is determined by the sense that the AGN activity limits the ISM mass that is eventually converted to stars by expelling it out of the galaxy. I showed that the Bondi accretion cannot operate during that phase (Section 2), and discussed the requirement that the ISM be in the hot phase (Section 3). As the radiative cooling time of the hot phase is relatively short (equation 10), to maintain a hot phase the infalling gas should be shocked at a radius of $R \gtrsim 5 \text{ kpc}$. Heating by the AGN facilitates the formation of the hot phase. As with CFs in clusters of galaxy, the heating and ejection of the ISM is done by jets, rather than by radiation.

The short radiative cooling time implies the formation of a CF in the inner region of the newly formed galaxy, but one that is substantially heated by the AGN activity. As Bondi accretion fails, the feeding of the SMBH is done via two channels. Like in the cold feedback mechanism in clusters of galaxies (Pizzolato & Soker...
cold blobs are falling from an extended region. The second channel is a cold supersonic inflow in the inner $\leq 1$ kpc of the galaxy, where cooling time is shorter than the inflow time; such an inflow was studied by Soker & Sarazin (1988). The AGN jets can be efficient enough to expel a large fraction of the inflowing gas and the gas in the hot phase (Soker 2009) out of the galaxy. Some of the cooling gas will form stars and feed the SMBH. A CF where a large fraction of the cooling gas is expelled from the inner region (and some fraction forms stars, and a small fraction is accreted by the SMBH) is termed a moderate CF model (Soker et al. 2001; Soker & David 2003). In Section 4.2 the moderate CF model in clusters of galaxies and at galaxy formation are compared, and summarized in Table 1.

The moderate CF model proposed here at galaxy formation can be applicable to the sample of obscured AGN studied by Brusa et al. (2009). The median value of $L_{AGN}/L_{Edd}$ in their sample is $\sim 2-10$ per cent. This gives a SMBH growth time of $\sim 10^9$ yr, similar to the growth time of the stellar population due to star formation. I propose that a moderate CF exists in these galaxies during the high star formation rate.

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