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Cooling Flows as a Calorimeter of AGN Mechanical Power

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ABSTRACT

The assumption that radiative cooling of gas in the centers of galaxy clusters is approximately balanced by energy input from a central supermassive black hole implies that the observed X–ray luminosity of the cooling flow region sets a lower limit on AGN mechanical power. The conversion efficiency of AGN mechanical power into gas heating is uncertain, but we argue that it can be high even in the absence of strong shocks. These arguments inevitably lead to the conclusion that the time averaged mechanical power of AGNs in cooling flows is much higher than the presently observed bolometric luminosity of these objects.

The energy balance between cooling losses and AGN mechanical power requires some feedback mechanism. We consider a toy model in which the accretion rate onto a black hole is set by the classic Bondi formula. Application of this model to the best studied case of M87 suggests that accretion proceeds at approximately the Bondi rate down to a few gravitational radii with most of the power (at the level of a few percent of the rest mass) carried away by an outflow.

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

1 INTRODUCTION

The radiative cooling time of gas in the central parts of rich galaxy clusters is much shorter than the Hubble time. Without an external energy source, the gas must cool below X–ray temperatures forming so-called "cooling flows" (see Fabian 1994 for a review). The fate of the gas, after it has cooled, is not clear and so far no unambiguous evidence for a massive repository of cold gas has been found. An excess photoelectric absorption in the cooling flow clusters derived from ROSAT and ASCA data (e.g. Allen 2000, Allen et al. 2001) can be interpreted as due to accumulation of the cold gas by the cooling flows over their lifetimes. This interpretation however has been questioned by Böhringer et al. (2002) based on the XMM-Newton data. Recent XMM-Newton and Chandra observations suggest that either gas does not cool below $\sim 1-3$ keV or it is somehow hidden from us (e.g. Fabian et al. 2001, Böhringer et al. 2001). One possibility, discussed for two decades, is that energy produced by AGN activity in the massive galaxy at the center of a cooling flow balances radiative losses of the X–ray emitting gas (see e.g. Binney & Tabor 1995). Such a picture would require fine tuning of the AGN power used for heating the gas since both too much or too little heating would imply either progressive heating or cooling of the X–ray emitting gas. If, however, such fine tuning is present, then it should be possible to use the X-ray luminosity of the cooling flow to estimate the the central AGN power. The gas in cooling flows is optically thin (at least in the continuum) and the heating efficiency of the gas by AGN radiation (see Ciotti & Ostriker 2001) is rather low. A more efficient source of heat is input from mechanical power, which we consider below.

Since the balance between radiative losses and gas heating by AGN mechanical input requires some feedback mechanism, we consider a simple model with the accretion rate onto a black hole set by the classic Bondi formula. Bondi accretion (Bondi 1952) is a hydrodynamical solution of spherically symmetric gas accretion without angular momentum onto a point mass. A supermassive black hole in an elliptical galaxy containing hot X–ray emitting gas is one site where accretion may actually proceed at the Bondi rate (Fabian & Canizares 1988). The gas density and temperature in these sources can be derived from X–ray observations. Then, if the mass of the black hole is known, the mass accretion rate can be estimated. The observed luminosities of the AGNs in these galaxies however are typically several orders of magnitude short of expected values, calculated using a standard $\sim$10% conversion efficiency from the rest mass of accreted material to radiation (Fabian & Canizares 1988). It was therefore suggested (e.g. Fabian & Rees 1995, Reynolds et al. 1996) that a hot ion torus forms around a black hole and accretion proceeds as an Advection Dominated Accretion Flow (ADAF; e.g. Narayan & Yi 1994). If the accretion rate is much smaller than the critical Eddington value then the ADAF solution predicts that a very small fraction of energy is radiated away. Recent theoretical developments of radiatively inefficient flows show that outflows can arise (Blandford & Begelman 1999) and/or an outward convective transport of energy may occur (e.g. Narayan, Igumenshchev & Abramowicz 1999; Quataert & Gruzinov 2000). Observations of supermassive black hole in elliptical galaxies in frame of the ADAF model and role of outflow are discussed e.g. by Di Matteo et al. (1999, 2000) and Loewenstein et al. (2001). For many sources, well-collimated jets are observed and (model dependent) estimates of the total mechanical power of the jets are much larger than directly observed luminosities of the AGN and the jet itself (e.g. Pedlar et al. 1990, Owen, Eilek & Kassim 2000).

2 COOLING FLOWS HEATED BY MECHANICAL AGN POWER

According to radio observations (e.g. Burns 1990), a large fraction (∼71%) of cD galaxies at the centers of cooling flows shows evidence for radio activity. This fraction is much higher than in non-cooling flow galaxies and suggests a possible link between the presence of cooling gas and the activity of a central supermassive black hole. Given that $\sim 10^8$–$10^{10} M_\odot$ black holes are likely to reside in these elliptical galaxies, one can imagine that these supermassive black holes, accreting matter at a rate well below the critical Eddington value, could provide the necessary amount of energy to offset cooling. Models involving gas heating by an AGN have been extensively discussed in the literature (e.g. Tucker & Rosner 1983, Binney & Tabor 1995, Soker et al. 2001, David et al. 2001, Jones et al. 2001). In the discussion below, we present a qualitative picture based particularly on the ROSAT, Chandra and XMM-Newton data on M87 and NGC 1275 (Böhringer et al. 1993, 1995, 2001, 2002, Fabian et al. 2000, Churazov et al., 2000, 2001).

We assume that most AGN power goes into an outflow and bubbles of hot, high entropy gas are created near the central engine. We further assume that direct microscopic heating (e.g. heating of the cluster gas by the high entropy gas in bubbles via thermal conduction) is inefficient. We are then left with the "mechanical" energy exchange between the bubbles and the cluster gas. The most important question here is what fraction of energy goes into sound waves which can escape the cooling flow region thus reducing the heating efficiency. From simulations of rising bubbles (e.g. Churazov et al. 2001, Brüggen et al. 2002, see also Rizza et al. 2000, Quilis, Bower and Balogh 2001), one can note that the characteristic dimensionless numbers like the Mach number $M = v/c_s$ or Froude number $F = v/\sqrt{gL}$ (where v is the characteristic velocity, c_s is the sound velocity, g is the gravitational acceleration and L is the characteristic length) are not very far from unity. This precludes an immediate conclusion on the character of generated disturbances and on the fate of the deposited energy. On the other hand the same argument suggests that while generation of sound waves certainly occurs during all stages of the lobe evolution, it is unlikely that the great bulk of energy is channelled into sound waves and that these waves carry away most of the energy (unless very special conditions are created).

2.1 The Late, Passive Stage of Bubble Evolution

Let us first consider the latest stages of bubble evolution. Buoyancy drives the bubbles upward with a subsonic velocity and the bubbles maintain approximate pressure equilibrium with the ambient gas. Initial energy deposition E_0 required to (slowly) inflate the bubble is the sum of internal energy of the bubble $1/(\gamma-1)PV$ and PdV work done by the expanding bubble on the cluster gas, where P is the pressure of the cluster gas, V is the volume of the bubble and γ is the adiabatic index of the hot gas inside the bubble. Thus $E_0 = \gamma/(\gamma-1)PV$. The buoyancy force acting on the bubble is $F = V\rho\frac{d\phi}{dr}$, where ρ is the density of the cluster gas and ϕ is the gravitational potential. Assuming that the bubble mass is very small the buoyancy force must be equal to the drag exerted on the rising bubble. The integral of the drag force over distance characterizes the mechanical energy exchange between the bubble and the ambient gas. Assuming that the bubble expands adiabatically during slow motion through the cluster atmosphere in hydrostatic equilibrium one can explicitly calculate how much energy was extracted from the bubble:

$$\Delta E = -\int V\rho\frac{d\phi}{dr}dr = E_0 - \frac{\gamma}{\gamma-1}PV = E_0[1-\left(\frac{P}{P_0}\right)^{1-1/\gamma}], \quad (1)$$

where P_0 and P are the initial and final pressure in the bubble respectively. Thus during their upward motion, the bubbles deposit their energy when crossing roughly a few scale heights. As an example, for $\gamma = 4/3$ and a pressure profile derived from the XMM-Newton data (Böhringer et al. 2001, Matsushita et al. 2002) half of the energy is lost by a bubble after reaching a distance of ∼ 20 kpc from the its origin.

An approximate estimate of how much energy goes into sound waves during the initial phase of the bubble's rise can be obtained assuming that the bubble instantly accelerates to a terminal velocity v and then maintains this velocity. For a solid sphere, Landau & Lifshitz (1986) give the energy emitted in sound waves as $E \sim \frac{\pi}{3}\rho R^3 v^2$, where ρ is the ambient gas density and R is the radius of the sphere. This energy is less than a quarter of the internal energy of the bubble $E_i \sim \frac{1}{(\gamma-1)\gamma}\frac{4}{3}\pi\rho R^3 c_s^2$, where c_s is the sound speed of the gas outside the bubble. After the initial acceleration, the motion of the bubble is subsonic and steady (as seen in the simulations) and we do not expect that the drag is predominantly due to the generation of sound waves and weak shocks. Actual values of the drag estimated from simulations (Churazov et al. 2001) also support this expectation. A large fraction of energy goes instead into the kinetic and potential energy of the entrained gas, turbulence in the wake of the bubbles, and possibly into internal gravity waves.

Given the steep entropy profiles in typical cooling flow clusters (the temperature is rising with radius while the density is deacreasing), large masses of entrained gas (even if accelerated to a fraction of the sound velocity) cannot travel a long distance with the rising bubbles (see Fig.10 in Churazov et al. 2001) and therefore kinetic energy can not efficiently "leak" outside the cooling flow region with the entrained gas.

Internal gravity waves are trapped within the inner region because the buoyancy frequency is a decreasing function of radius in clusters (e.g. Balbus & Soker 1990, Lufkin, Balbus, & Hawley 1995). The buoyancy (Brunt-Väisälä) frequency N can be written as

$$N^2 = \frac{g}{\gamma}\frac{\mathrm{d}\ \ln s}{\mathrm{d}\ r}, \tag{2}$$

where $s = P/\rho^{\gamma}$ is the gas entropy, r is the radius, g is the gravitational acceleration, and P is the pressure. For M87, the buoyancy frequency can be estimated directly using the gas temperature and density profiles derived from the XMM-Newton data (Bohringer et al. 2001, Matsushita et al. 2002) under the assumption that the gas is in hydrostatic equilibrium. These estimates give $N \sim 1.2\ 10^{-7}$, $3.5\ 10^{-8}$, $1\ 10^{-8}$ rad/y at radii of 2, 10 and 50 kpc respectively. Thus, the frequency of the internal waves excited in the inner region is larger than the buoyancy frequency in the outer parts and the waves are reflected back into the central region.

Finally, we note that for subsonic turbulence (created in the wake of a rising bubble), the ratio of the rates of generation of sound waves and dissipation is (Landau & Lifshitz, 1986)

$$\frac{\varepsilon_s}{\varepsilon_d} \sim \left(\frac{v}{c_s}\right)^5 \ll 1, \tag{3}$$

where v is a characteristic velocity and c_s is the sound speed.

Note also that, as pointed out by Pringle (1989), sound waves themselves are focused into the central region due to the decrease in the sound speed at small radii. This effect may enhance the dissipation of the generated sound waves within the central cooling region. In the presence of steep temperature gradients, sound waves traveling at large angles to the radius may even be trapped in the cooling flow region. The condition for trapping requires the ratio of the square of the radius to the temperature, $r^2/T(r)$, be a decreasing function of radius. However the observed change of temperature (and associated change of the sound velocity) is rather modest for M87 (see e.g. Böhringer et al. 2001) and the condition for trapping is not satisfied. The effect of focusing is also modest and this mechanism is unlikely to strongly affect the energy balance.

Thus after the gas passes through a phase of complex rearrangements and mixing, a significant fraction of the initial bubble energy is dissipated within the cooling flow region. Although sound waves are inevitably generated during this process, they can carry away only a fraction of the energy comparable to that which is dissipated.

2.2 Active, Early Stage of Bubble Formation

At earlier stages of a bubble's (radio lobes) formation, shocks are likely to occur. If the energy injection occurs in a small region of undisturbed cluster gas then strong shocks will be sent into the medium. Strong shocks are efficient in energy dissipation and there would be direct heating of the gas as it passed through any strong shock. In a spherically symmetric cluster atmosphere, with a density profile typical of a cooling flow ($\rho \sim 1/r$), the strength of the shock decreases and it evolves into a sound (compression) wave which can carry away some part of the shock energy. Strong shocks leave behind relatively compact regions of high entropy gas which contain significant fractions of the energy. The numerical value of this energy fraction depends on the gas adiabatic index and the radial profile of the ambient gas parameters. However, an analogy with the Sedov solution for a strong explosion suggests that the fraction of the shock energy deposited is "of the order of several times 10%" (Zeldovich & Raizer 1966). The further transfer of energy from this localized high entropy region to the rest of the cluster gas follows the same processes as already described above.

Weak shocks on the other hand do not dissipate energy efficiently and they may be the major source of energy leakage from the cooling flow region. When the lobe passes through the transonic expansion stage, a significant fraction of the injected energy can escape the cooling flow region. But even during this stage, the fraction of energy which remains in the form of internal energy within the lobe (and potential energy of the displaced gas) is unlikely to be much less than half the total.

The bottom line is that the fraction of mechanical energy deposited by an AGN and dissipated *within the cooling flow region* is high. For simplicity in the discussion below we assume that it is equal to unity.

3 BONDI ACCRETION AND THE COOLING FLOW LUMINOSITY

The assumption that the whole cooling flow region is in a state of quasi-stationary equilibrium requires the injected mechanical power to match the radiative cooling losses of the thermal gas. Therefore a feedback mechanism is required which must provide global stable equilibrium between heating and cooling. We discuss below a toy model in which the classic Bondi formula regulates the accretion rate onto the black hole and provides a link between the gas parameters and the mechanical power of an AGN.

The rate of spherically symmetric adiabatic gas accretion without angular momentum onto a point mass can be written as (Bondi 1952):

$$\dot{M} = 4\pi\lambda(GM)^2 c_s^{-3}\rho, \tag{4}$$

where λ is a numerical coefficient, which depends on the gas adiabatic index γ (for $\gamma = 5/3$ the maximal valid value of λ allowing steady spherically symmetric solution is $\lambda_c = 0.25$), G is the gravitational constant, M is the mass of the black hole, $c_s = \sqrt{\gamma\frac{kT_e}{\mu m_p}}$ is the gas sound speed and ρ is the mass density of the gas. Adopting $\lambda = \lambda_c = 0.25$ and substituting a reasonable set of parameters one can write:

$$\dot{M}_B = 10^{-2}\left(\frac{M}{3\times10^9 M_{\odot}}\right)^2 \left(\frac{n_e}{0.1\ cm^{-3}}\right)\left(\frac{T_e}{1\ keV}\right)^{-3/2} M_{\odot}\ y^{-1} \tag{5}$$

Here we use parameters appropriate for M87: $M = 3\times 10^9 M_{\odot}$ (Ford et al. 1994, Macchetto et al. 1997), typical (minimal) temperature near the center $T_e \sim 1\ keV$ and characteristic central density $n_e \sim 0.1\ cm^{-3}$ (Böhringer et al. 2001, Matsushita et al. 2002). Given the angular resolution of XMM-Newton these values correspond to the region of 1-2 kpc in size. A quick check of the Chandra M87 images shows that the X–ray surface brightness is not steeply increasing from ∼1.5 kpc down to 0.3-0.2 kpc, where the emission from the nucleus and the jet start to dominate. This suggests that the XMM-Newton data provide a reasonable estimate of the density and temperature in the core region. The cooling time of the gas with these parameters ($t_{cool} \sim \frac{3/2P}{n_e^2\Lambda(T)} \sim 10^7 - 10^8$ y, where P is pressure and $\Lambda(T)$ is a cooling function) is much longer than the characteristic accretion flow time scale ($t_{flow} \sim \frac{R_B}{c_s} \sim$ few 10^5 y) near the Bondi radius:

$$R_B = 2GM/c_s^2 = 0.1 \left(\frac{M}{3\times10^9 M_\odot}\right)\left(\frac{T_e}{1\ keV}\right)^{-1}\ kpc \qquad (6)$$

Therefore (see e.g. discussion by Nulsen and Fabian 2000) the flow can be treated as nearly adiabatic well outside the Bondi radius thus validating the usage of Bondi formula (4).

The above estimate of the accretion rate is a factor of 150 lower than a similar estimate made by Di Matteo et al. (2000). This is at least partly attributable to a lower density and a higher (adiabatic) sound velocity adopted here.

Assuming that it is Bondi accretion which is actually powering an AGN one can obtain an approximate estimate of the accretion efficiency:

$$\eta = \frac{L_X}{\dot{M}_B c^2} \approx 0.05 \left(\frac{\dot{M}_B}{0.01\ M_\odot\ y^{-1}}\right)^{-1}\left(\frac{L_X}{3\times10^{43}\ erg/s}\right) \qquad (7)$$

Here we adopted the X–ray luminosity of the cooling flow region in M87 of 3×10^{43} ergs s^{-1} (Peres et al. 1998). From the above expression one can conclude that if (i) the mass accretion rate is approximately characterized by the Bondi formula and (ii) a large fraction of the energy is carried by an outflow which is eventually dissipated into heat in the cluster gas then a few percent of the rest mass of accreted material has to be channeled into a jet or outflow. If the density at the Bondi radius is a factor of ∼10 higher as suggested by Di Matteo et al. (2000), then the efficiency will be lower, possibly as small as $\lesssim 1\%$. Such an efficiency is still very high and simple outflow (Blandford & Begelman 1999) or convection dominated flows (Narayan, Igumenshchev & Abramowicz 1999) where most of the material does not reach the innermost region cannot easily account for such a high energy ejection efficiency (if the accretion rate at the outer boundary is set by the same Bondi rate).

The Bondi accretion rate is proportional to the ratio $\frac{n_e}{c_s^3} \propto \frac{n_e}{T_2^{3/2}} \propto s^{-3/2}$, where s is the entropy of the gas at the Bondi accretion radius. Thus for a given black hole mass and cooling flow luminosity, the entropy of the accreting gas should have a certain value so as to provide the same amount of energy which is emitted in X–rays:

$$s \approx 3.5 \left(\frac{M}{10^9 M_\odot}\right)^{4/3}\left(\frac{\eta}{0.1}\right)^{2/3}\left(\frac{L_X}{10^{43}\ erg/s}\right)^{-2/3}\ kev\ cm^2 \qquad (8)$$

A lower/higher entropy than this value implies too much/little heating to offset gas cooling over the whole cooling flow region. Interestingly (but naturally given that this is just another form of equation (7)), this value of entropy is close to that found in the cores of cooling flows. Thus energy input is controlled by the minimum value of the gas entropy in the cooling flow region.

It should be stressed that although observed amounts of cold gas and star formation rates in the cD galaxies are lower than the values expected for the mass deposition rate inferred from the X-ray data, they are clearly enhanced in the central cooling flow galaxies. This suggests that some fraction of the gas is able to cool down, well below X-ray temperatures. The presence of cold gas in the central region may invalidate our simple estimates of the Bondi accretion rate based on the X-ray determined density and temperature of the gas.

4 DISCUSSION

We speculate below on the implications of the assumptions made in the previous two sections:

- **A** The time averaged mechanical power of an AGN is approximately equal to the radiative losses of the whole cooling flow region.
- **B** The accretion rate given by the Bondi formulae can be used as an (outer) boundary condition near the Bondi radius.

4.1 Efficiency of Accretion

Comparison of the accretion rate at the Bondi radius (eq. 5) and the observed cooling flow luminosities implies (at least for M87) a high accretion efficiency – of the order of a few percent of the rest mass (see eq. 7). Therefore accretion should proceed with a rate $\dot{M} \approx const \approx \dot{M}_B$ from the Bondi capture radius R_B down to a few gravitational radii. An outflow therefore should start very close to the black hole. This in turn can be considered as an indirect argument in favour of an outflow in the form of a jet. Interestingly, estimates of jet mechanical power in some well studied cases (like M87 or NGC1275) give very high values (e.g. Pedlar et al. 1990, Owen, Eilek & Kassim 2000) comparable to the total X–ray luminosity of the cooling flow region. Pushing this speculative argument to the limit, we can conclude that since our assumptions **A** and **B** mean that the mechanical power of the AGN should adjust to the radiative losses, then the jet power depends on the accretion rate and therefore accretion is the major source of a jet's power in these objects. An alternative possibility is that accretion serves as a trigger for jet formation and the time averaged power is regulated through the duty cycle of the AGN.

Numerical simulations of cluster formation (e.g. Frenk et al., 1999) suggest that successive mergers may lead to gas bulk motions with typical kinetic energies at the level of ∼ 15% of the gas thermal energy even for relatively relaxed clusters. The presence of bulk motions in the cooling flow region implies that gas has angular momentum. If the gas captured at the Bondi radius has small, but nonzero angular momentum, then at smaller radii the character of the accretion flow may change significantly from the spherically symmetric Bondi solution. The behavior of the flow in this region would depend on the effective viscosity and the angular momentum transport and the flow may settle on the geometrically thin (cold) or geometrically thick (hot) solutions. Although the mechanical power, required by our assumption **A** is large, the observed luminosities (e.g. from M87 or NGC 1275) are much lower than the standard $0.1\dot{M}c^2$. Therefore an ADAF-like solution is needed in this picture (at least in the inner region) and the standard geometrically thin disk solutions (Shakura & Sunyaev 1973) extending down to the marginally stable orbit can be definitely excluded (Fabian & Canizares 1988, Fabian & Rees 1995). We note here that this problem is not only a consequence of our assumptions, but directly follows from the the comparison of jet power estimated by Pedlar et al. (1990) or Owen, Eilek & Kassim (2000) and observed luminosities of the central objects in M87 or NGC1275.

4.2 Global Stability

In the absence of a heat source, the total luminosity of the cooling flow region is defined by the conditions (density and temperature) at the cooling radius, i.e., at the radius where the cooling time approximately equals the lifetime of the cluster. If the mechanical power of the AGN fed via Bondi accretion is indeed the source of energy which balances the cooling of the gas, then the actual AGN power depends on the entropy of the gas near the Bondi capture radius, i.e. at a distance of ~ 0.1 kpc from the central black hole. On dynamical time scales, the cooling flow region adjusts to have the lowest entropy gas at the bottom of the potential well. Too low values of the entropy would increase the mechanical power of the AGN above the radiative losses of the whole region and eventually will increase the minimum entropy present in the system up to an equilibrium value. Too high values of the entropy would mean that the power of the AGN is too low to offset global radiative losses and eventually low entropy gas will appear in the central region and the power of the AGN will increase.

4.3 Quasi-continuous Injection

In the model discussed above, the time averaged AGN power is fixed by the cooling flow luminosity. However the appearance of the central region of the cooling flow may depend on the amplitude of the AGN power variations. For example, for very powerful but rare flares, strong shocks are driven into the cluster gas and large bubbles should be formed with a distinct envelope of hot, compressed gas (e.g. Heinz, Reynolds & Begelman 1998). Recent Chandra and XMM-Newton data, however, do not show widespread evidence for shocks in the cooling flow region (e.g., Fabian et al. 2000, McNamara et al. 2000, Böhringer et al. 2001, 2002, David et al. 2001). These results rather favour a scenario with more quasi-continuous injection of energy. In this case (at least for spherical geometry), strong shocks should be confined to spatially smaller regions. There are, however, examples where the observed properties are best explained by strong shocks driven by a powerful outburst – the most spectacular one is perhaps NGC 4636 (Jones et al. 2001) in which both the surface brightness morphology and the temperature structure suggest a strong shock. With further observations of a large sample of objects it should be possible to decide on whether sporadic or quasi-continuous energy injection dominates.

4.4 Sketch of the Cooling Flow Region

Based on the above discussion, it is possible to outline the basic properties of a cooling flow heated by buoyant bubbles, which are quasi-continuously generated by an AGN. Bubbles are created in the innermost region and are assumed to be filled with a hot, radio emitting plasma. The size of a typical bubble is set by injection power, gravity, and parameters of the cluster gas in such a way that the lifetime of a bubble due to buoyancy is comparable with the expansion time of the bubble due to injection power. For M87 and NGC1275 this corresponds to a size in the range of few – 10 kpc. The bubbles have much larger entropy than the ambient gas and they rise through the whole cooling flow region. Perhaps the most important process operating in the innermost region is not a net heating, but entrainment which continuously removes the low entropy gas from the central region (Churazov et al. 2001, Nulsen et al. 2001). If initial bubbles are created along some preferred direction, then bubble induced gas motion may resemble the motion of air in the room with a heater: the higher entropy gas rises along one direction while lower entropy gas accretes along others. This means that the radial entropy profile of a cooling flow does not necessarily develop a flat core.

When crossing a few scale heights, the bubbles i) lose their energy through drag forces and ii) decrease in radio brightness significantly. At this stage, bubbles can be identified as X–ray surface brightness "holes" that are not associated with strong radio emission (Churazov et al. 2000, Fabian et al. 2000, McNamara et al. 2001). The dissipation of energy extracted from the bubbles is distributed spatially with no obvious "heating" features e.g. shock waves. As seen from the simulations of the bubbles in M87, the velocity with which the bubbles rise is smaller than the sound velocity of the cooling flow gas, but not by a large factor. Therefore the bubbles pass through the cooling flow during time interval only slighly longer than a sound crossing time t_s. This is at least an order of magnitude shorter than a typical gas cooling time t_c. An assumption that radiative losses of the gas is compensated by the (efficient) dissipation of the bubbles energy then implies that the total volume of the bubbles created during one cooling time of the gas is approximately equal to the cooling flow volume (or in other words the total energy of the bubbles is equal to the total energy of the cooling flow). Therefore a volume filling factor of the bubbles within the cooling flow region is approximately $t_s/t_c \ll 1$.

Thermal instabilities can take place on a background of extensive convective motions. Overdense (cool) lumps of thermal gas, entrained by the bubbles and rising from (or falling back to) the central region might produce filamentary structures, stretching radially from the galaxy. One possible example of such a filament may be found in A1795 (Cowie et al. 1983, Fabian et al. 2001).

5 CONCLUSION

We show that even in the absence of strong shocks a significant fraction of the energy of radio lobes inflated by an AGN is dissipated in the cooling flow region. Only a comparable (but not overwhelmingly dominant) fraction of the mechanical power of an AGN may escape the cooling flow region in the form of sound waves.

If the the radiative cooling of the gas in the centers of galaxy clusters is balanced by energy input from a central supermassive black hole, then the observed X–ray luminosity of the cooling flow region sets a lower limit on the AGN mechanical power. The required power is much larger than the observed luminosity of these AGNs, but is consistent with (model dependent) estimates of jets power in some objects.

We describe a toy model with the AGN power determined by Bondi accretion for spherically symmetric accretion. Comparison of the accretion rate predicted by the Bondi formula with the luminosity of the cooling flow region in M87 suggests a high transformation efficiency of rest mass of accreted material into the mechanical power of an outflow at the level of a few percent.

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