FEEDBACK HEATING WITH SLOW JETS IN COOLING FLOW CLUSTERS

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ABSTRACT

We propose a scenario in which a large fraction or even most of the gas cooling to low temperatures of \( T < 10^4 \) K in cooling flow clusters gains energy directly from the central black hole. Most of the cool gas is accelerated to nonrelativistic high velocities, \( v_j \approx 10^3 - 10^4 \) km s\(^{-1}\), after flowing through, or close to, an accretion disk around the central black hole. A poorly collimated wind (or a pair of poorly collimated opposite jets) is formed. According to the proposed scenario, this gas inflates some of the X-ray–deficient bubbles, such that the average gas temperature inside these bubbles (cavities) in cooling flow clusters is \( kT_b \lesssim 100 \) keV. A large fraction of these bubbles will be very faint or undetectable in the radio. The bright rims of these weak smaller bubbles will appear as ripples. We suggest that the X-ray ripples observed in the Perseus cluster, for example, are not sound waves but rather the rims of radio-faint weak bubbles that are only slightly hotter than their environment. This scenario is incorporated into the moderate cooling flow model; although not a necessary ingredient in that model, it brings it to better agreement with observations. A cooling flow does exist in the moderate cooling flow model, but the mass cooling rate is \( \lesssim 10\% \) of that in old versions of cooling flow models.

Subject headings: cooling flows — galaxies: clusters: general — intergalactic medium — X-rays: galaxies: clusters

1. INTRODUCTION

Recent Chandra and XMM-Newton observations of cooling flow (CF) clusters of galaxies have failed to detect the large amounts of cool gas predicted by the old versions of the CF model (e.g., Tamura et al. 2001; Peterson et al. 2003, 2004; Molendi & Pizzolato 2001), reducing by at least 1 order of magnitude the expected mass cooling rate to low temperatures. These results raise several questions. Do CFs occur at all? If they do, what is the actual mass cooling rate? What is the fate of the cool gas? In many clusters an unhindered radiative loss would lead to a sizeable CF in a few times \( 10^8 \) yr. Since this does not seem to happen and some reheating is required (e.g., Fabian 2003), what is the nature of this heating mechanism?

In this paper we adopt the framework of the moderate CF model to address the fate of the cool gas, and we suggest that a large fraction (and in some cases most) of the cool gas is being ejected back to the intracluster medium (ICM) by the active galactic nucleus (AGN) operating at the central cD galaxy. The approach we adopt here differs from those adopted by most authors (e.g., Binney & Tabor 1995; Tucker & David 1997; Ciotti & Ostriker 2001; Binney 2004; Omma et al. 2004; Mathews et al. 2004; for more references, see Peterson et al. 2004), in that we do consider a CF, albeit a moderate one. We conclude that the best agreement with the available data occurs if the jets are not well collimated.

In \( \S \) 2 we sketch the envisaged scenario, putting it in the appropriate framework of the moderate CF model. In \( \S \) 3 we review some hints to slow jets. Among them, a key role is played by the hot bubbles observed with Chandra in several CF clusters. In \( \S \) 4 we discuss the properties of slow and massive jets, and we learn that the bubbles’ properties seem to require slow and dense jets, which imply a mass cooling rate of \( \approx 10 M_\odot \) yr\(^{-1}\) in large CF clusters. In other words, the bubbles imply the presence of a CF. We summarize in \( \S \) 5.

2. THE PROPOSED SCENARIO

We start this section by recalling some important features of the moderate CF model (for more details, see Soker et al. 2001; Soker & David 2003), as well as some other relevant ingredients for our proposed model. The moderate CF model, which was proposed before the new results from Chandra and XMM-Newton were available (hence we avoid referring to an old version of the CF model as “standard”), is different from many earlier proposed processes whose aim was to prevent CFs in clusters of galaxies altogether (Soker et al. 2001; Soker & David 2003). The main ingredient of the moderate CF model is that the effective age, i.e., the time elapsed since the last major disturbance of the ICM inside the cooling radius \( r_c \approx 100 \) kpc, is much shorter than the cluster age (e.g., Binney & Tabor 1995; Binney 2004; Soker et al. 2001). The cooling radius is defined as the place where the radiative cooling time equals the cluster age. Originally, the heating in the moderate CF model was proposed to be intermittent (Soker et al. 2001), but the basic idea can hold for a steady heating, or heating in short intervals (Binney 2004).

In the moderate CF model most of the gas within the CF resides in the hottest phase, which is prevented from cooling continuously and attaining a steady-state configuration by being reheated (Soker & David 2003; Kaiser & Binney 2004). This results in a mass cooling rate that decreases with decreasing temperature, with a much lower mass cooling rate at the lowest temperatures. The limit on the cooling rate below a temperature \( T_{\text{min}} \) inferred from X-ray observations is \( < 20\% \) of the mass cooling rates cited in the past (e.g., Fabian et al. 2002a; Molendi & Pizzolato 2001; Peterson et al. 2003). In some cases, however, cooling to low temperatures is observed, as in the CF clusters A2597 (Morris & Fabian 2005) and A2029 (Clarke et al. 2004). In A2597 both extreme-UV and X-ray observations indicate a mass cooling rate of \( \approx 50 M_\odot \) yr\(^{-1}\), which is \( \approx 0.2 \) of the value quoted in the past based on ROSAT X-ray...
observations (see the discussion in Morris & Fabian 2005). Some fraction of the gas may cool to lower temperatures by heat transfer to optical-emitting gas, further reducing the X-ray emission from gas residing at temperatures of $T \lesssim T_{\text{min}} \approx 1$ keV; the energy transfer can be via mixing (e.g., Oegerle et al. 2001; Fabian et al. 2001, 2002a; Johnstone et al. 2002; Bayer-Kim et al. 2002) and/or heat conduction (Soker et al. 2004; Soker 2004b). Intermittent heating, which is part of the moderate CF model, probably occurs by AGN activity. In a recent paper McNamara et al. (2005) found a huge deficient X-ray bubble pair in the cluster MS 0735.6+7421, which suggests that an intermittent heating over a large timescale might play a role. In the moderate cluster CF model, the agreement between star formation rate and mass cooling rate can be quite good. Wise et al. (2004) and McNamara et al. (2004), for example, find the cooling rate within $r \approx 30$ kpc of the CF cluster A 1068 to be about equal to the star formation rate there ($20-70$ $M_\odot$ yr$^{-1}$).

Another plausible element of the moderate CF model is that the entire inner CF region supplies the cold gas accreted to the black hole (Pizzolato & Soker 2004). Namely, the feedback between heating and cooling occurs with the entire cool inner region, $r \lesssim 5-30$ kpc, in what we term a “cold-feedback model.” In the proposed scenario (Pizzolato & Soker 2004) nonlinear overdense blobs of gas, $\delta \rho/\rho_0 \gtrsim 2$, i.e., $\rho/\rho_0 \gtrsim 3$, in this inner region cool on such short timescales that they are removed from the ICM before the next major AGN heating event in their region. Some of these blobs cool and sink toward the central black hole, while others may form stars and cold molecular clouds. This mechanism can work on the condition that the blobs have a small angular momentum, or they would be prevented from accreting onto the central black hole and fueling its activity. This issue has been discussed in a separate paper (Pizzolato & Soker 2004); here we just summarize the main conclusions. The cold blobs may stem directly from ICM disturbances driven by an earlier AGN activity but also from galaxies that are mass stripping (Soker et al. 1991). Since the galaxies do not have an ordered bulk motion, the mass stripped from them is also unlikely to maneuver and organize into an ordered flow with high net angular momentum. Therefore, if a circular flow like a disk forms, it cannot be very large, say, $\sim 10^2$ pc as in M87 (Harms et al. 1994; Ford et al. 1994). The orbit of a dense blob subjected to gravity and the friction drag force has a circularization radius whose size is in broad agreement with this value (Pizzolato & Soker 2004). Besides, in the cold feedback model the cold gas is expected to accrete from regions not too far from the center (a few tens kpc at most), so the accreting flow should not have a large angular momentum from the outset. Therefore, the blobs’ angular momentum is not high enough to prevent them from accreting in a timescale shorter than or comparable to the cooling time, which keeps running the cooling/accretion feedback loop.

In this paper we suggest that a large fraction (and in some cases most) of the accreting cool gas is being ejected back to the ICM by the AGN. This idea solves some of the problems related to the questions posed above. In particular, the slower and more massive collimated wind (namely, a poorly collimated jet pair, hereafter referred to simply as jets) deposits its energy in the inner region (Binney 2004), as required by recent observations that limit the degree of mixing (Böhringer et al. 2004), and it can carry more energy than inferred from radio observations (Binney 2004). In this paper we extend this idea of slow and massive, poorly collimated jets and incorporate it to be an important element in the duty cycle of the moderate CF model. The proposed scenario is fundamentally different from the scenario of Nulsen (2004) or that of Binney (2004; see also Omma & Binney 2004). In those papers, most or all of the mass that is accreted to the central black hole comes from the hot phase, $T \approx 10^7$ K. Hence, the mass that is ejected in the jets is small compared to the mass assumed to be cooling to $T \approx 10^4$ K in the moderate CF model. In the proposed scenario, on the other hand, we address the question of the fate of the cold gas, arguing that a nonnegligible fraction of it is ejected back to the ICM at high nonrelativistic velocities. In those papers the duty cycle, or feedback process, is determined by energy considerations alone, while in our scenario the mass is also a factor in the duty cycle.

Our proposed scenario is also different from the circulation flow proposed by Matthews et al. (2004); in their scenario the gas does not cool below X-ray emission temperature. This is a significant difference, as basically they do not consider the presence of a CF at low temperatures ($T < 10^4$ K), while we do. In common with their model, we ascribe significance to mass as well as energy transport in both inward and outward direction.

The cool ICM flows to the center, and if it has an angular momentum, it may form an accretion disk about the central black hole. A standard geometrically thin, optically thick accretion disks (à la Shakura-Sunyaev) truncated at the last marginally stable orbit around the black hole has a radiative efficiency $\eta \approx 10\%$, corresponding to a bolometric luminosity

$$L_{\text{accer}} \approx 5.7 \times 10^{45} \text{ ergs s}^{-1} \left( \frac{\eta}{0.1} \right) \left( \frac{M}{M_\odot \text{ yr}^{-1}} \right).$$

Such bright disks are not common, which forces us to assume that the disk’s radiative efficiency is low. The disk may be truncated at several Schwarzschild radii from the hole (e.g., it may be evaporated by magnetic fields), which reduces $\eta$ in equation (1) by orders of magnitude. Alternatively, the disk may be radiatively inefficient; i.e., it does not radiate most of the energy converted by the viscous dissipation, for example, an advection-dominated accretion flow (ADAF) or an adiabatic inflow–outflow solution (ADIOS; Narayan & Yi 1994; Blandford & Begelman 1999). Omma et al. (2004) assume an ADAF flow in the framework of their simulations. In these kinds of accretion flow, most of the incoming flux is gravitationally unbound to the black hole and can therefore be pushed back as an outflow or a wind. A possible issue is that ADAFs cannot exist for high accretion rates (Quataert et al. 1999). There is the possibility, however, that the disk is composite, with the ADAF component confined in the inner part, the outer being an ordinary accretion disk (e.g., Quataert et al. 1999). Disks like these may exist even for high accretion rates and may also support the required outflow.

In the next section we start by reviewing some hints that the outflowing jets are slow. It seems as if the properties of bubbles require slow and dense jets, which imply a mass cooling rate of $\gtrsim 10 M_\odot \text{ yr}^{-1}$ in large CF clusters. Namely, the bubbles imply the presence of a CF. We then estimate the relevant parameters and summarize by listing some predictions of the proposed model.

3. THE TEMPERATURE OF HOT BUBBLES

We list below some pieces of evidence that some bubbles are inflated mainly by nonrelativistic jets; i.e., the temperature of the gas inside some bubbles is $T_b \lesssim 100$ keV. A population of radio-emitting relativistic electrons may exist as a result of the
contribution from a relativistic jet as well. In other cases, such as the large bubbles in M87, the inflating jets are relativistic (Forman et al. 2003), and the nonrelativistic component is lacking.

1. In most clusters only a lower limit determination of the hot bubbles temperature is possible (Blanton 2004). Some examples are $T_b > 15$ keV for Hydra A (Nulsen et al. 2002), $T_b > 11$ keV for Perseus (Schmidt et al. 2002), and $T_b > 20$ keV for A2052 (Blanton et al. 2003). We are aware of only the case of MKW 3S where a bubble temperature was measured (Mazzotta et al. 2002). In this cluster a surface brightness depression located at a distance of $r_b \sim 100$ kpc from the cluster center has a temperature $T_b \sim 6-10$ keV (Mazzotta et al. 2002). In both Hydra A (David et al. 2001) and A2052 (Blanton et al. 2001) the pressure drops by a factor of $f_p \approx 0.1$ from the inner region to $r \approx 100$ kpc. For an adiabatic expansion with a constant ratio of the bubble to external pressure, the temperature inside the bubble drops by a factor of $f_T = f_p^{1/3} \approx 0.4$. If we assume that the bubble in MKW 3S was inflated in the inner region and then was buoyantly rising and adiabatically expanding, then its initial temperature was $T_{100} \sim 15-25$ keV. The preliminary results of McNamara et al. (2005) show that the two large X-ray-deficient bubbles in the cluster MS 0735.6+7421 are only slightly hotter than their environment, strengthening the results above. A word of caution about these measurements is in order, however. It is extremely difficult to measure the temperature of the material in the ICM bubble with the current data. The geometry of the cavities is never known well enough to allow an accurate deprojection; moreover, it is unknown whether the emission stems from the body of the cavity or from its rims. If we were to adopt a more conservative viewpoint, we could say that the current temperature measurements are consistent with the view that these blobs are filled with hot plasma.

2. The pressure in the bubbles inferred from the radio emission and the assumption of equipartition between magnetic and relativistic particles is lower than the ambient pressure (Blanton 2004). This hints (but does not prove) that the bubbles are not entirely relativistic, because the bubbles are in pressure equilibrium with their environment.

3. Some AGNs have been observed to blow nonrelativistic winds, with speeds down to 24,000 km s$^{-1}$ (PDS 456; Reeves et al. 2003; PG 1211+143; Pounds et al. 2003; however, see McKernan et al. 2004 for some possible problems). The identification of an even slower wind (~1000 km s$^{-1}$) in the LINER NGC 1097 is more problematic (see Storchi-Bergmann et al. 2003 and references therein).

On the theoretical side, Binney (2004) lists some arguments in support of a slow outflow. According to Binney (2004), in many cases the relativistic jet carries a small fraction of the mass and energy in the outflow, and in some systems no relativistic jet is present even when slower outflow occurs. In their bubble-inflation simulations, Omma & Binney (2004) take the wind speed to be in the range (2.8–4) $\times 10^4$ km s$^{-1}$, with a mass-loss rate of $1 M_\odot$ yr$^{-1}$, and Omma et al. (2004) find $v_j = 10,000$ km s$^{-1}$ and a mass-loss rate into the jet of $2 M_\odot$ yr$^{-1}$. In many models of quasars the velocity of the wind blown by the disk is in the range ~$10^3$ to $3 \times 10^4$ km s$^{-1}$ (Elvis 2000; Crenshaw et al. 2003 and references therein). There are other models that predict slow (~$10^3$ km s$^{-1}$) winds, the most recent one being the Begelman & Celotti (2004) model. In the model proposed byNicastro (2000), the wind velocity decreases from ~20,000 to ~1000 km s$^{-1}$ as the mass accretion rate increases; in this model the high accretion rate expected in CF clusters may result in slow winds. In Seyfert galaxies, mass-loss rates from the black hole vicinity as large as ~$1 M_\odot$ yr$^{-1}$ have been inferred (Crenshaw et al. 2003). The outflow of the absorbing gas starts at distances as small as ~0.01 pc from the black hole, indicating origin from the accretion disk. The possibility of slow jets from the nucleus (3C 317) of the CF cluster A2052 was raised recently by Venturi et al. (2004).

The slow wind velocities suggested above leads to bubble temperatures of $kT_b \leq 100$ keV. Using the expression given by Castor et al. (1975) for the expansion of an interstellar bubble (Bicknell & Begelman [1996] also applied this expression to study the bubble formed by the radio jet in M87), the temperature inside the bubble is

$$kT_b \approx 0.15 \mu m u_1 v_j^2 = 100 \left( \frac{v_j}{10^4 \text{ km s}^{-1}} \right)^2 \text{ keV},$$

where $v_j$ is the jet velocity, and $\mu m u_1$ the mean mass per particle. This temperature implies a low density in the bubble, assuming pressure equilibrium with the ICM. Even for $v_j = 4000$ km s$^{-1}$, the bubble temperature is ~5 times higher than the ambient temperature in the inner regions of CF clusters (typically ~1–3 keV). This means a bubble density of $n \approx 0.2$ times the ambient density and emissivity $n^2 \approx 0.04$ times that of the ambient medium. This low emissivity cannot be detected by current X-ray telescopes.

If, as assumed here (following Binney 2004), the AGN blows gas with a spectrum of velocities, then the bubble is multiphase. In some cases the fastest blown gas has relativistic speeds, and the bubble is detectable in the radio. The formation process of the bubble is likely to lead to some internal motion within the bubble. This internal motion determines the mixing of the different gas phases at later times, and the magnetic field topology and evolution determines local heat conduction. The evolution at late times is hard to predict and probably very hard to simulate as well. We do expect that the phases will be mixed among themselves and later on with the ICM, hence heating the ICM. As with other bubbles models, the bubbles themselves heat the ICM by doing work on the ICM and by lifting cool ICM medium from the center.

We stress that in this model slow winds do not exclude the occurrence of fast, relativistic jets. Indeed, many of the best examples of ICM cavities are clearly associated with radio lobes (e.g., Hydra-A: McNamara et al. 2000; Perseus: Fabian et al. 2002b). Slow winds and relativistic jets may coexist; the former carry most of the energy (Binney 2004), and the latter carry the fuel of the synchrotron emission from the relativistic electrons in the X-ray cavities.

4. JET PROPERTIES

4.1. The Mass Flow Rate into the Jets

Combining the estimated energy of bubbles (or bubble pairs) with the typical nonrelativistic velocity assumed in the previous section yields the mass ejection rate. Birzan et al. (2004) give the observed mechanical luminosity of 16 clusters. The jets’ kinetic luminosity will be equal to several times the power $L_{\text{mech}}$ calculated by Birzan et al. from the bubbles volumes of $PV$, where $P$ is the pressure and $V$ is the bubbles’ volume. Most luminous clusters therefore reside in the range $L_{\text{mech}} \sim (0.3–3) \times 10^{44}$ ergs s$^{-1}$, with possible higher values if the pressure inside the bubbles is higher than in their surroundings (Birzan et al. 2004), or if some energy is in shocks formed by the inflated
bubbles (Forman et al. 2003; McNamara et al. 2005). Numerical simulation requires the power to be on the higher side $E_j \approx 5 \times 10^{44}$ erg s$^{-1}$ (e.g., Dalla Vecchia et al. 2004; Ohama & Binney 2004). Also, the power of jets in AGNs can reach a power of $E_{j,\text{max}} \approx 10^{47}$ ergs s$^{-1}$ (e.g., Rawlings & Sanders 1991). We therefore scale the averaged energy injected by the AGN in CF clusters with values higher than the energy directly observed (Binney 2004) and take it to be $5 \times 10^{44}$ ergs s$^{-1}$. Scaling with typical values and using equation (2), the mass-loss rate into the jets is

$$M_j \approx 15 \left( \frac{E_j}{5 \times 10^{44} \text{ ergs s}^{-1}} \right)^{1/3} \left( \frac{kT_b}{100 \text{ keV}} \right)^{-1/3} \left( \frac{1}{M_\odot \text{ yr}^{-1}} \right).$$

In MKW 3S the temperature inside the bubble $T_b$ has been estimated (Mazzotta et al. 2002), and we take the value calculated in the previous section for the initial value of the temperature, $T_{b0} \approx 20$ keV; we also take $E \approx 10^{44}$ ergs s$^{-1}$ found by Birzan et al. (2004). From these we find $M_j \approx 15 M_\odot$ yr$^{-1}$. This is more than the X-ray–inferred mass cooling rate of $M_{\text{cool}} < 2 M_\odot$ yr$^{-1}$ (Birzan et al. 2004). However, in MKW 3S the bubbles are not so prominent as in other clusters and may represent a relatively old ejection event.

### 4.2. Jet Propagation

On the basis of § 3 of Soker (2004a), we note the following properties in regards to the heavy jets. It is assumed that the slow collimated wind (or poorly collimated jet) has a wide opening angle, measured from the symmetry axis of the jet, of $\alpha \approx 1$. The expansion velocity of the jet’s head $v_h$ is given by the following expression as long as $v_h \ll v_j$:

$$v_h \approx \left[ \frac{E_j}{\pi (1 - \cos \alpha)^2 v_j \rho_c} \right]^{1/2} = 1200 \left( \frac{E_j}{5 \times 10^{44} \text{ ergs s}^{-1}} \right)^{1/2} \times \left( \frac{v_j}{10^4 \text{ km s}^{-1}} \right)^{-1/2} \left( \frac{1 - \cos \alpha}{0.5} \right)^{-1/2} \times \left( \frac{\rho_c}{10^{-25} \text{ g cm}^{-3}} \right)^{-1/2} \left( \frac{z}{5 \text{ kpc}} \right)^{-1} \text{ km s}^{-1},$$

where $\rho_c$ is the ambient density and $z$ is the distance of the jet’s head from its source, measured along the jet’s symmetry axis. Note that the jet is scaled with an opening angle of $\alpha = 60^\circ$ (from its symmetry axis; the full opening angle is $120^\circ$). For these parameters the jet becomes subsonic in the ICM at a distance of $\sim 10$ kpc. The subsonic jet expands to the side, ensuring the formation of a large bubble. A large opening angle, although not a necessary condition to inflate a bubble, facilitates the formation of a large bubble close to the center.

A bubble can be formed before the jet’s head becomes subsonic if the shocked material in the jet expands faster than the jet’s head (Soker 2004a). The condition on the opening angle of the jet for that to occur is given by equation (14) of Soker (2004a). We change the variable in that equation as follows. From equation (4), the distance of the jet’s head as function of time is given by

$$z \approx 3.4 \left( \frac{1}{10^6 \text{ yr}} \right)^{1/2} \text{ kpc.}$$

We substitute the value of the time from the last equation into equation (14) of Soker (2004a) to derive the condition to inflate a bubble via the mechanism discussed in Soker (2004a):

$$\alpha \approx 50^\circ \left( \frac{E_j}{5 \times 10^{44} \text{ ergs s}^{-1}} \right)^{3/10} \left( \frac{v_j}{10^4 \text{ km s}^{-1}} \right)^{-1/2} \times \left( \frac{\rho_c}{10^{-25} \text{ g cm}^{-3}} \right)^{-3/10} \left( \frac{z}{5 \text{ kpc}} \right)^{-1/5}.$$

From equations (4) and (6) we see that the large opening angle of the jet (a poorly collimated jet) facilitates bubble formation (Soker 2004a). In the proposed scenario a bubble is formed at a distance of $z \approx 10$ kpc from the source of the jet. The large opening angle assumed here is different from the heavy slow jet simulation of Mazzotta et al. (2002).

The large opening angle implies that the jet, when expanded outward, interacts with a substantial fraction of the ICM in its vicinity. The jet (and the bubble it forms) pushes outward the ICM that is cooler and denser than the ICM that the bubble reaches at a later time. Such a wide open angle flow might account for dense shells observed around some bubbles, e.g., in A2052 (Blanton et al. 2001).

With our proposed scenario, in which many small and weak bubbles that are only slightly hotter than their environment exist, we turn to the deep X-ray image of the Perseus CF cluster (Fabian et al. 2003). Many bright arcs, which are termed ripples, are seen in this cluster. They were interpreted by Fabian et al. (2003) as sound waves. However, we suggest that these are actually the bright rims of a stack of weak flattened bubbles accumulated in the past, which have been flattened by the resistance of the environment ICM they push through. This is supported by noting the following:

1. The rims of the two inner X-ray–deficient strong bubbles and the rim of the outer strong bubble resemble the X-ray ripples in both shape and size, except that they are brighter than the ripples.
2. Some ripples, when considered as geometric spherical arcs, have their center off from the cluster center.
3. While sound waves are expected to expand to all directions, some ripples are very short.

One possible prediction of our proposal that the ripples are actually rings of weak bubbles is that very weak radio emission will be detected between some ripples, similar to but much weaker than the radio emission in X-ray–deficient bubbles.

On the other extreme, a slow jet can be well collimated; hence, it propagates along a narrow cone into the ICM. Let $\beta$ be defined such that the jet expands into a solid angle $\Omega_j = 4\pi\beta$. For $\alpha = 12^\circ$, for example, $\beta = 0.01$. By neglecting the magnetic pressure inside the jet and relativistic effects, hence $E_j = M_jv_h^2/2$, the speed of the jet’s head is determined by pressure equilibrium on its two sides. An approximate relation is obtained if we consider only ram pressures, $\rho_j(v_j - v_h)^2 = \rho_c v_h^2$, where $\rho_j$ is the ICM density, $\rho_c = M_j/(4\pi r^2 v_h^2)$ is the density inside the jet, $v_j$ is the speed of the gas inside the jet, $v_h$ is the speed of the jet’s head, $M_j$ is the mass-loss rate into one jet, and $r$ is the distance of the jet’s head from its origin (e.g., Krause 2003). For $v_j \gg v_h$, the jet’s head propagation speed is given by

$$v_h = \frac{v_j}{(\rho_j/\rho_c)^{1/2} + 1} \approx 600 \left( \frac{E_j}{5 \times 10^{44} \text{ ergs s}^{-1}} \right)^{1/2} \times \left( \frac{v_j}{10^5 \text{ km s}^{-1}} \right)^{-1/2} \left( \frac{\beta}{0.01} \right)^{-1/2} \times \left( \frac{n_a}{0.1 \text{ cm}^{-3}} \right)^{-1/2} \left( \frac{r}{5 \text{ kpc}} \right)^{-1} \text{ km s}^{-1}.$$
The power of one jet is scaled according to that of Hydra A as given by Birzan et al. (2004), the total ambient number density is scaled with that of Hydra A as given by David et al. (2001), and the jet speed is scaled with a fast velocity of \( v_j = 0.33c \).

The last equation shows that jets like those in Hydra A become subsonic at \( \sim 5 \) kpc from their origin if they are very fast. This explains the observations that the jets in Hydra A turn into lobes. But what is the reason for the sharp transition from a well-collimated jet to radio lobes in Hydra A? We note from the last equation that a slow jet, even if weak, might stay supersonic to large distances. For example, for a jet with \( E = 10^{43} \) ergs \( s^{-1} \) and \( v_j = 3000 \) km \( s^{-1} \), we find \( (\rho_0/\rho_j)^{1/2} \approx 2 \), and the exact solution of the last equation is \( v_b \approx 1000 \) km \( s^{-1} \) at a distance of \( r = 5 \) kpc. We therefore propose that the current jets in Hydra A were preceded by collimated slow and dense jets that opened a tunnel to a distance of \( r \sim 5 \) kpc, through which the current jets are expanding almost undisturbed. When the current jets leave these tunnels, they interact with the ICM, become subsonic, and lose their collimation. A slow jet with these parameters \( (E = 10^{43} \) ergs \( s^{-1} \) and \( v_j = 3000 \) km \( s^{-1} \)) has a mass-loss rate of \( 3.5 \) \( M_\odot \) \( \text{yr}^{-1} \), namely, the two proposed slow jets blow \( \sim 7 \) \( M_\odot \) \( \text{yr}^{-1} \) back to the ICM. To propagate to a distance of \( \sim 5 \) kpc, the slow jets were active for a few times \( 10^6 \) yr. Hence, in total, they blew a nonnegligible mass back to the ICM.

### 4.3. Spectral Signature of the Outflow

What are the observational characteristics of the slow, poorly collimated outflow? Usually, the winds blown by AGNs are revealed by their absorption of the underlying continuum in the UV or X-rays (e.g., PG 1211+143: Pounds et al. 2003; PDS 456: Reeves et al. 2003; NGC 1097: Storechi-Bergmann et al. 2003; see also Crenshaw et al. 2003 for a recent review). Since the outflows we have dealt with in this paper are not very hot at their outset \( (10^5\sim 10^6 \) K), their ionization degree should also allow detection in the UV or in X-rays, as in ordinary AGNs. Since the wind remains relatively cold on rather small, subkiloparsec scales, the actual detectability of the wind may be complicated by other factors, like the absorption by intervening clouds. The slow outflow is active during a small fraction (10%–30%) of the time. Hence, most clusters will not show any signature of the slow wind.

### 5. SUMMARY

The purpose of this paper is to propose a plausible new element for the moderate CF model. We propose (speculate) that a large fraction, or even most, of the mass that cools to low temperatures is ejected back to the hot ICM via an accretion disk around the central black hole. The main ingredients of the moderate CF model are as follows: (1) the effective age of the CF is much shorter than the cluster age because of intermittent heating, (2) intermittent heating most likely occurs via AGN activity, (3) only in the very inner regions is the flow in a steady-state phase, and (4) cooling to low temperatures \( (T \leq 10^4 \) K) occurs at a rate much lower than that in older versions of CF models (see §1).

This proposed scenario is based on several observations and theoretical considerations (§3) that hint at either bubble temperatures of \( T_b \lesssim 100 \) keV or at the possibility that AGNs can blow relatively slow winds (jets), 1000 km \( s^{-1} \) \( \lesssim v_j \lesssim 10,000 \) km \( s^{-1} \). With the lower energy per ejected unit mass (eq. [2]), the outflowing mass required to account for the energy in the bubbles may contain a significant fraction of the mass cooling to low temperatures (eq. [3]). In the proposed scenario, the average power of the AGN is much higher than that inferred from radio emission or even from the energy content of the large bubbles. Some mass will be blown at \( v_j \approx 3000\sim 5000 \) km \( s^{-1} \), forming small bubbles, with density not much smaller than their surroundings. Birzan et al. (2004) find that the energy associated with X-ray-deficient bubbles does not generally explain the low mass cooling rate, unless the bubbles contain only a small fraction of the total kinetic energy. The proposed speculative scenario accounts for this extra energy.

In the proposed scenario most of the cooling mass stays in the inner region \( r \approx 10\sim 50 \) kpc of the CF cluster, as most bubbles do not rise to large radii. This is compatible with the implication that there is no vigorous mixing in CF clusters (Böhringer et al. 2004). We stress that there is no ICM wind; we simply propose that some fraction of the jets (or collimated outflow), which inflate some of the bubbles, are blown at a relatively low speed and contain a significant fraction of the mass cooling to temperatures of \( \lesssim 10^4 \) K. This element of the moderate CF model improves the agreement of the model with observations. However, this element is not necessary for the moderate CF model.

The proposed scenario predicts the following:

1. As an element of the moderate CF model, it requires that some mass cools to low temperatures but at moderate average rates \( M_{\text{cool}} \approx 1\sim 50 \) \( M_\odot \) \( \text{yr}^{-1} \).
2. The temperatures of the gas in large bubbles is, in most cases, \( T_b \lesssim 100 \) keV.
3. In many clusters small bubbles exist that are only slightly hotter than their surroundings. Such bubbles may reveal themselves as patchy, low X-ray-emitting regions, such as those observed in M87-Virgo (see the X-ray image by Young et al. 2002).
4. Weak radio emission might be observed between X-ray ripples, such as the ripples discovered by Fabian et al. (2003) in the Perseus cluster. We recognize, however, that these observations may be difficult, chiefly on account of confusing projection effects.
5. Subrelativistic, \( v_j \approx 10,000 \) km \( s^{-1} \) flow from a relatively extended region around the central black hole of CF clusters exists from time to time (or presently, for 10%–30% of the cooling-flow clusters).
6. At least in some favorable cases, we do expect to detect such outflows thanks to their absorption in the UV or X-ray spectrum, as observed in the winds blown by other AGNs.

The first three predictions can be tested with current X-ray telescopes. We predict that deep X-ray observations of the inner regions of CF clusters will reveal (1) emission from gas cooling below \( \sim 1 \) keV, as in A2597 (Morris & Fabian 2005) and A2029 (Clarke et al. 2004); (2) some X-ray emission from some bubbles, implying that their density is not much lower than their ambient density; and (3) small bubbles scattered around, only slightly hotter than their surroundings.

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