

Cooling Flows or Heating Flows?

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It is now clear that AGN heat cooling flows, largely by driving winds. The winds may contain a relativistic component that generates powerful synchrotron radiation, but it is not clear that all winds do so. The spatial and temporal stability of the AGN/cooling flow interaction are discussed. Collimation of the winds probably provides spatial stability. Temporal stability may be possible only for black holes with masses above a critical value. Both the failure of cooling flows to have adiabatic cores and the existence of X-ray cavities confirm the importance of collimated outflows. I quantify the scale of the convective flow that the AGN Hydra would need to drive if it balanced radiative inward flow by outward flow parallel to the jets. At least in Virgo any such flow must be confined to $r \lesssim 20$ kpc. Hydrodynamical simulations suggest that AGN outbursts cannot last longer than ~ 25 Myr. Data for four clusters with well studied X-ray cavities suggests that heating associated with cavity formation approximately balances radiative cooling. The role of cosmic infall and the mechanism of filament formation are briefly touched on.

1. Introduction

How important are AGN for the dynamics of cooling flows? Are cooling flows in approximate steady states, or do they evolve significantly over a Hubble time? The debate of these issues is more than a decade old, but the recent spectacular increase in the quality of the observational data has revived it and stimulated a new generation of simulations of AGN/cooling-flow interaction. Here I review these developments. In Section 2 I summarize the observational situation. Section 3 discusses the physics of AGN/cooling-flow interactions; each component affects the other and it is important to assess whether these interactions are stabilizing or otherwise. Section 4 gives preliminary conclusions from a program of large numerical simulations of jet-induced heating that we are carrying out in Oxford. Section 5 examines the balance between heating and cooling from an empirical point of view and concludes that, when averaged over ~ 100 Myr, heating and cooling *are* in balance. Section 6 sums up and briefly discusses cosmic infall and filament formation.

2. The Story So Far

Data from the *Chandra* and *XMM-Newton* missions have convinced pretty much everyone that the intergalactic medium in clusters is not a multi-temperature medium: although the quality of the fit to the spectrum of an annulus can often be improved by including radiation from plasma at two temperatures rather than one, the temperature of the cooler component never differs by more than a factor of a few from that of the higher-temperature component, and the emission measure of the hotter component always dominates by more than an order of magnitude (Sanders this meeting). Moreover, the imaging data show significant inhomogeneities within annuli that require two-temperature fits, and it seems likely that the second temperature component merely com-

pensates for temperature gradients within each annulus. These results falsify the picture of distributed mass dropout that dominated cooling-flow studies for nearly two decades.

Within a few kpc of the cluster center, cool gas *is* detected. Gas at $\lesssim 100$ K is detected in the rotation lines of CO (Lazareff et al. 1989; Mirabel et al. 1989; Reuter et al. 1993; Edge 2001). Gas at a few thousand Kelvin is detected in the rotation-vibration transitions of H₂ (Donahue et al. 2000; Edge et al. 2002). Gas at a few times 10^4 K is detected through optical emission lines (Lynds 1970; Cowie et al. 1983; Heckman et al. 1989; Conselice et al. 2001). Gas at $\sim 10^6$ K is detected in soft X-rays (Fabian et al. 2003b). The spatial distribution of the observed emission lines and soft X-rays is consistent with the cold gas being organized into filaments, within which the temperature increases continuously from the center outwards. The filaments have complex velocity fields and it seems very unlikely that they are in dynamical equilibrium within the cluster potential. The mass of gas at say a tenth of the cluster's virial temperature is at least an order of magnitude smaller than the mass of such gas that was predicted to accumulate over the cluster lifetime by the distributed dropout model. Moreover, is much more centrally concentrated than it was predicted to be.

In parallel with destroying the concept of distributed mass dropout, the new data provide clear evidence that active galactic nuclei are pumping energy into cooling flows. Specifically, the new data show that cavities in the X-ray emitting gas, like that discovered by Böhringer et al. (1993) in the Perseus cluster, are common (Fabian et al. 2000; Blanton et al. 2001; McNamara et al. 2001; Nulsen et al. 2002; Heinz et al. 2002). The low X-ray emissivity within these cavities must arise because the pressure within them is dominated either by very hot thermal plasma or by relativistic particles and their associated magnetic fields, or by both. Radio emission from

many cavities shows that these objects are regions of enhanced energy density from ultra-relativistic particles and fields, which establishes a clear connection between the cavities and activity by AGN within the cluster.

The title of this conference, ‘The Riddle of Cooling Flows’, reflects a widespread feeling that these observational results are unexpected and perplexing. I do not share this feeling because I have been arguing for over a decade (i) that distributed mass dropout makes no sense physically and (ii) that cooling can occur only at the center, where it will generate outbursts by the AGN, so (iii) there is a fundamental symbiosis between cooling flows and AGN. I say this not merely to brag (though I do) but to make the point that far from being puzzling, the data from *Chandra* and *XMM-Newton* are very much in line with expectation if one applies sound physical principles to systems in which there is gravitationally trapped cooling gas.

A decade ago my student Gavin Tabor worked out detailed models of cooling flows in elliptical galaxies rather than clusters of galaxies because I felt surer of the physics in smaller systems: the timescales are very short in elliptical galaxies and the current impact of system formation and cosmic infall can be much more securely neglected. Unfortunately, the quality of the data for elliptical-galaxy cooling flows is still very poor [the exceptions being Cen A (Kraft et al. 2003) and NGC 4636 (Kahn et al. 2002)] but I have no doubt that a similar picture applies in ellipticals, and strongly suspect that the well known correlations between nuclear black hole masses and global properties of bulges involves the dynamics of galaxy-sized cooling flows in an essential way (Binney 2003b).

3. AGN As Heaters

We now know for certain that massive black holes lurk at the centers of cooling flows. They will accrete ambient gas. The natural estimate of the rate at which a black hole accretes from an atmosphere of given pressure P and sound speed c_s is the Bondi (1952) accretion rate

$$\dot{M} = 4\pi \left(\frac{GM}{c_s^2} \right)^2 \rho c_s = 4\pi G^2 M^2 \frac{\gamma P}{c_s^5}. \quad (1)$$

This accretion rate is extremely sensitive to the sound speed of the atmosphere near the black hole. This sensitivity makes it plausible that the black hole is a thermostatically controlled heater: when radiative cooling lowers c_s , the accretion rate rapidly rises and releases accretion energy that reheats the atmosphere. Notice that the accretion rate depends on c_s even more sensitively than the fifth power manifest in equation (1) because P will rise slightly as c_s declines. However, the dependence of \dot{M} on c_s through P is weak, and below I shall ignore it.

3.1. Stability

Suppose a cooling flow is in a state in which heating balances cooling at each radius and consider the stability of this state in both a spatial and a temporal sense. The question with regard to spatial stability is this. Suppose the heating weakens for some reason, then the net

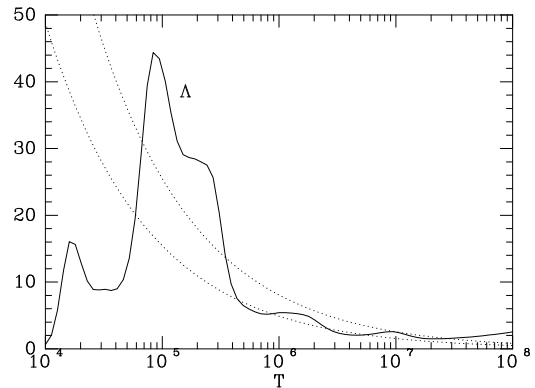


FIG. 1.— Full curve: the cooling coefficient $\Lambda(T)$ for a plasma with 0.4 of solar abundances. Dashed curves: curves proportional to $T^{-1/2}$ that intersect the full curve at $T = 3.5$ and 4.5×10^5 K.

cooling that ensues will make the density profile steeper than it was. Will the system recover from this excursion when the heating rate later increases? The answer to this question is ‘no’ if the AGN merely returns to its former power: that power balanced the unmodified cooling rate, so it will be less than the enhanced current cooling rate. But if the AGN returns to work with renewed vigor after its rest, refreshed perhaps by the enhanced Bondi accretion rate, then I think it is plausible that the system can recover its old density profile provided it heats the ambient medium with jets. For in this case the spatial distribution of the injected energy depends on the density profile of the cooling gas. Enhanced density at small radii leads to the jets disrupting closer to the AGN, and thus increases the fraction of the AGN’s power that is dissipated at small radii. If the increased concentration of the jets’ energy deposition is large enough, gas near the AGN will expand faster than gas further out, and the density profile will flatten to its former shape. Clearly, this mechanism needs to be quantified by hydrodynamical simulations.

To investigate the temporal stability of heated cooling flows, consider the differential equation

$$\frac{dT}{dt} = \frac{1}{T^2} \left(\frac{A}{\sqrt{T}} - \Lambda(T) \right). \quad (2)$$

This equation describes the temperature of a system that is heated at a rate that scales $\sim T^{-5/2}$ (cf. eq. 1) and is cooled at a rate that scales as $\sim T^{-2}\Lambda(T)$, as does a plasma that is confined by a constant pressure. In Figure 1 the two terms inside the big bracket on the right of equation (2) are plotted, the dotted curves showing the first term for two values of the constant A . Thermal equilibrium is possible when the dotted and full curves cross; for the equilibrium to be stable the full curve has to have the larger slope at the point of intersection. We see that for A less than some maximum value, stable equilibria exist at temperatures less than that of the peak in the cooling curve at 83 000 K. For any value of A at least one point of stable equilibrium exists at a higher temperature. In the case of the upper dotted curve, a unique high-temperature equilibrium lies at 2.7×10^7 K. For the lower dotted curve there are stable equilibria at 10^6 K

and 5×10^6 K. The stability of an equilibrium depends on the difference in the slopes of the intersecting curves, so the high-temperature equilibria are only weakly stable in a linear sense, and, in the case of the lower dotted curve, can be destabilized by quite modest variations in the parameter A .

The low- and high-temperature equilibria differ strongly in the system's accretion rate and luminosity: the low-temperature equilibrium has the larger luminosity by a factor $f^{5/2}$, where f is the ratio of the temperatures; in the case of the upper dotted curve in Figure 1 this factor is 3.4×10^6 .

Equation (2) is only a toy equation that gives some insight into a complex dynamical system that is governed by non-linear hydrodynamic equations. The temperature that appears in the equation should be interpreted as the temperature of the accreting plasma at the point inside the black hole's sphere of influence where the Kepler speed equals the sound speed. This temperature will not be significantly lower than that, T_{\min} , associated with the Kepler speed at the edge of the black hole's sphere of influence. Only in very small galaxies will T_{\min} be less than 10^5 K. Hence real accreting black holes may not possess the low-temperature equilibrium that the toy equation (2) predicts. What the equation does correctly predict for systems with small values of A is their *instability* at all temperatures in the range 0.8 to 5×10^5 K and roughly half of the temperatures from there up to 2×10^7 K. This wide-ranging instability may well lead to runaway growth of the accretion rate and luminosity.

The coefficient A that determines what equilibrium points exist reflects the relative importance of heating and cooling. An increase in the mass of the accreting black hole within a given cooling flow will be reflected in an increase in the best-fitting value of A , and may move A to a value at which only a stable high-temperature equilibrium is possible. Hence our toy equation suggests that black holes above a critical mass (that depends on the parameters of the cooling flow) have a single moderately stable state of low luminosity, while lower-mass black holes have one or more low-luminosity states of marginal stability and are otherwise liable to experience runaway growth of their luminosity.

3.2. Output Channels from AGN

We still do not have a clear picture of what happens when a given mass of gas falls onto a massive black hole. Equation (1) is a plausible estimate of the rate at which gas falls from the center of a cooling flow into the force-field of the central black hole. But how much energy is released in consequence, and in what form does it emerge?

The efficiency $\epsilon = E/(\dot{M}c^2)$ with which accretion by a black hole releases energy is controversial. Comparison between the space density of massive black holes and the integrated luminosity density of quasars implies $\epsilon > 10\%$ in luminous quasars (Yu & Tremaine 2002). Controversy rages as to whether a similar efficiency applies to accreting systems that are faint in the optical and UV. It has long been recognized that implausibly large luminosities are derived for many massive black holes if the rate (eq. 1) is multiplied by an efficiency anywhere

near as high as 10% (Fabian & Canizares 1988). One school of thought argues that around these black holes, which include Sgr A* at the Galactic center and the black holes at the centers of all nearby cooling flows, electrons fail to heat and the ions carry the accretion energy over the event horizon before the electrons can radiate it. To my mind this picture, like distributed mass dropout, is physical nonsense (Binney 2003a). A much more plausible explanation for the low luminosities of many black holes is that offered by Blandford & Begelman (1999): a wind from the surface of the accretion disk carries off much of the energy and angular momentum that is released by accretion. Moreover, the wind carries away most of the mass that falls within the sphere of influence of the black hole at the rate given by equation (1). The upshot is rather a small rate of mass flow over the event horizon, and the release of nearly all the associated accretion energy as a sub-relativistic wind.

We are familiar with synchrotron-emitting jets emanating from the nuclei of the central galaxies of cooling flows. It is natural to assume that the Blandford-Begelman wind is collimated on parsec scales and to identify this with the observed jet. But this association is dangerous! The jets from M87 and similar galaxies have significant bulk Lorentz factors γ , while a wind from the accretion disk is expected to be non-relativistic. Consequently the observed jets probably arise through vacuum breakdown in the ergosphere of a rotating black hole (Blandford & Znajek 1977) and are not directly connected to the subrelativistic wind from the disk. The observed jets are conspicuous because shocks in them readily generate synchrotron-emitting electrons, but they may be ephemeral side-shows. In particular, they may flicker on and off on the short timescale associated with the ergosphere, and we should expect to see systems in which the wind is present, but there is no relativistic jet. Sgr A* may be just such a system. The connection between the mechanical luminosity of the sub-relativistic wind and the synchrotron luminosity of the source may be weak or non-existent. Jet luminosities derived from observations of relativistic jets, such as that for M87 by Reynolds et al. (1996) constitute lower limits on the total mechanical luminosity of the AGN.

3.3. Collimation

We should keep an open mind about the extent to which the sub-relativistic wind is collimated. The less well collimated it is, the more locally it will couple to the thermal plasma of a cooling flow. Tabor first investigated the case of local coupling that would apply if the wind were essentially uncollimated (Tabor & Binney 1993). In this case the wind would shock near the black hole to produce a hot cavity – a similar cavity would be produced in the situation envisaged by Ciotti & Ostriker (1997, 2001), in which the flow is heated by inverse Compton scattering of photons. An entropy inversion is created in which specific entropy decreases outwards. The region in which this occurs is convectively unstable. As in an early-type star, convection cells soon eliminate this gradient, and the system settles to approximate hydrostatic equilibrium in a configuration that has a constant-entropy

core. Tabor & Binney constructed models in which this constant entropy core joined at some radius to a steady cooling-driven inflow.

The new data have shown that in cooling flows specific entropy is not constant near the center: in reality the mass $M(\sigma)$ with entropy index $\sigma = P\rho^{-\gamma}$ less than some value fits the formula

$$M \propto (\sigma - \sigma_0)^\epsilon \quad (3)$$

with σ_0 a constant and $\epsilon \sim 1.5$ (Kaiser & Binney 2003a,b). This finding suggests that the outflow from the AGN that heats a cooling flow is collimated into jets. A jet simultaneously heats the ambient medium at several different radii, and thus offers an alternative to convection as a means of carrying heat from the AGN out to the sites of radiative cooling. The observed cavities in the X-ray emitting gas provide direct evidence for collimation.

3.4. FR I or FR II Sources?

The radiation of X-rays makes the cluster gas more centrally concentrated, and if unchecked will produce a central cooling catastrophe in a typical cooling flow within several hundred Myr. Binney & Tabor (1995) conjectured that at some stage the central AGN ‘winds back the clock’ and restores the cooling flow to the state it was in at an earlier time. A few powerful outburst could set the clock back several Gyr each, or many weaker outbursts could set the clock back tens of Myr each.

Fanaroff-Riley (FR) II radio galaxies have powerful jets that end in a hot spot on the periphery of the source, while the weaker jets of FR I sources break up or bend dramatically near the center of the source. FR II sources are thought to have kinetic luminosities ~ 100 times the cooling-flow luminosity and lifetimes ~ 100 Myr, so each outburst injects energy comparable to that radiated in X-rays over a Hubble time. Consequently, they can be responsible for reheating cooling flows only if they radically reduce the cooling flow’s central density to the point at which the central cooling time becomes almost as long as the Hubble time. Reynolds et al. (2002) and Basson & Alexander (2003) have simulated the impact on intra-cluster gas of FR II sources and shown that most of the energy is injected well beyond the cooling radius, so FR II sources do not reduce the density within the cooling radius sufficiently.

Eilek (this meeting) notes that the great majority of sources at the centers of cooling flows are of the FR I type. Hence they have relatively small luminosities and jets that become unstable at a small fraction of the cooling radius. In Virgo Owen et al. (2000) have mapped the diffuse synchrotron emission to unprecedentedly low surface-brightness levels, and shown that the emission has a sharp edge at $\sim 0.4r_{\text{cool}}$. This finding suggests that not only the current outburst, but all its predecessors have dissipated their energy within this radius. Thus we have a consistent picture in which regular weak outbursts by FR I sources replenish the energy radiated in the innermost part of the cooling flow. Our group in Oxford is concentrating on simulating the impact of weak FR I sources (Omma et al. 2003), and below I give preliminary conclusions from this work.

The existence and dynamics of FR II sources implies that the thermostat on a massive black hole can fail: a rapid drop in the central sound speed c_s , caused, for example, by a major accretion event, will provoke a powerful nuclear outburst. However, precisely the power of the jets will cause them to burst out of the core of the cooling flow and thus strongly diminish their ability to heat and expand the gas that is causing the outburst. Thus while cooling flows may be stable to small perturbations, sufficiently large perturbations may cause them to flare up dramatically.

3.5. Local Heating Versus Entrainment

One can imagine two rather different routes by which an AGN might establish a steady state. In the most straightforward route it would inject into each radial shell heat that balanced the local cooling. In practice a major contributor to the heating of the X-ray emitting plasma would be the dissolution of cavities. Another possibility is that entrainment of ambient gas would establish an outflow along the jet axis that balanced a radiatively driven inflow elsewhere. The synchrotron map of Virgo by Owen et al. (2000) cited above limits the applicability of this model in the case of Virgo: since outflow appears not to extend beyond $r \sim 40$ kpc, the regime in which dissolution of cavities is unimportant cannot be relevant outside $r \sim 20$ kpc, although it might apply at small radii. Heating by dissolving cavities *must* be important at radii of order 30 kpc.

To understand how cavities dissolve, imagine pouring a tanker full of olive oil into the ocean. The oil would quickly flow over the ocean surface to form a huge sheet, only a few molecules thick. In a similar manner the fluid inside a cavity spreads out azimuthally when it reaches the level at which the ambient medium has a density similar to itself. What makes the process more complex than the spreading of oil on water is the absence of a sharp density discontinuity in the ambient medium analogous to the water/air interface, and ongoing turbulent mixing of hot and cold plasma as the cavity rises and dissolves.

To investigate the regime of balanced in- and out-flows that might apply far inside the cooling radius, it is useful to calculate a different \dot{M} profile to one that is familiar from the discredited mass-dropout picture. Consider a body of gas, instantaneously in hydrostatic equilibrium, in which the specific entropy density s increases outwards. In the absence of heating, the rate at which mass moves through specific entropy s is

$$\left. \frac{dM}{dt} \right|_s = \frac{\partial m}{\partial s} \frac{ds}{dt}. \quad (4)$$

I evaluate the first derivative on the right using equation (3), and the second derivative follows from the luminosity per unit mass

$$L = \frac{\Lambda(T)n_e^2}{n_e m_p} = T \frac{ds}{dt}. \quad (5)$$

Fig. 2 shows the resulting \dot{M} profile for Hydra. This profile resembles the \dot{M} profile of traditional mass-dropout theory in increasing with radius, but there are important differences of detail between the two profiles. First,

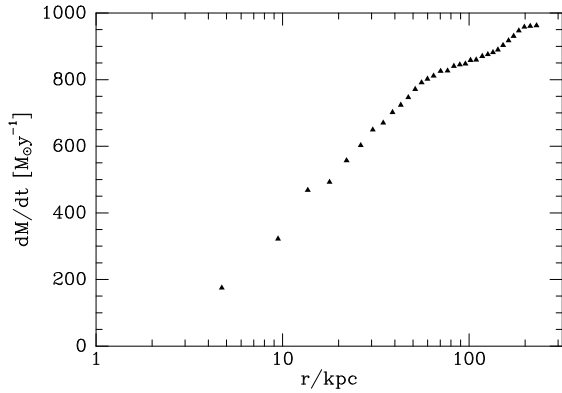


FIG. 2.— The \dot{M} profile for the Hydra cluster from the data of David et al. (2000) and equations (4) and (5). The metallicity is assumed to be $0.4Z_{\odot}$.

interior to $r \sim 50$ kpc the profile of Fig. 2 shows that

$$\dot{M} \propto \log(r/r_0) \quad (6)$$

with $r_0 \sim 2.5$ kpc, while a conventional \dot{M} profile has $\dot{M} \propto r$. Thus the mass flux rises more slowly with radius than in the conventional picture. Second, the profile in Fig. 2 reaches values of \dot{M} that are about twice as large as those reached by the traditional profile for this cluster (David et al. 2000). Both results arise because we are calculating not the rate at which mass crosses a given radial shell, but the rate at which it passes through a given specific entropy. Since we have allowed for cooling but not heating, the temperature and entropy at a given radius are decreasing, so the radius at which a given value of the specific entropy is attained is moving outwards at the same time that each physical shell of gas is moving inwards. Hence, we are determining the mass flux of a flow with respect to a moving frame of reference. The frame moves fastest near the center, so that is where \dot{M} is most enhanced with respect to the traditional value.

If radiatively driven inflow is balanced by outflow along the jet, the mass flux carried by the outflow would have to increase by $(d\dot{M}/ds)ds$ between the radii at which the specific entropy of the inflowing gas moved from s to $s + ds$. If we assume that equation (6) holds and that the radial density profile can be approximated by a power law (in practice $\rho \propto r^{-1.5}$ in a wide range of r), then one can show that

$$\frac{d\dot{M}}{ds} = \text{constant for } \sigma \gg \sigma_0. \quad (7)$$

The numerical value of the mass-flow rate along the jet axis would be given by Fig. 2. It would be very large even at the small radii ($r \lesssim 30$ kpc) at which this picture might apply.

4. The Oxford Simulations

Advances in computer hard- and software finally make it feasible to run the simulations of cooling-flow heating that I would have liked Tabor to run a decade ago. Then we had to settle for spherically symmetric hydrodynamics, which, as we stressed, inevitably excluded much of the key physics. We now use ENZO (Bryan & Norman

1997), a code which does hydrodynamics on adaptive Cartesian grids. As far as we are aware, ours is the only work on this problem that uses three-dimensional adaptive grids to achieve kpc-scale resolution at the center of a box that encompasses the entire cluster.

For the reasons given in Section 3.4, we concentrate on low-power outbursts and seek to understand the dynamics of cavities that are confined to within the cooling radius. Previous simulations aimed at this problem (Churazov et al. 2001; Quilis et al. 2001; Brüggén & Kaiser 2001; Brüggén et al. 2002; Brüggén & Kaiser 2002) have simply deposited energy at some arbitrarily chosen location. In our simulations (Omma et al. 2003) we inject both energy and momentum in such a way that jets form within the simulation, and these then heat the ambient medium in two dynamically determined regions. In the simulations of Reynolds et al. (2002) and Basson & Alexander (2003), the regions of heating were also dynamically determined. However, these simulations differ from ours in two respects: (i) their jets were > 100 times more luminous than ours, and (ii) their jets were imposed through inflow boundary conditions on a sphere that excluded the cluster center from the computational region. Our algorithm for jet formation avoids the use of internal boundary conditions.

Our main conclusions from this ongoing work are the following

1. The duration of an AGN outburst, rather than its power, is what determines the range of radii within which its energy is finally deposited. Unless AGN outbursts are of rather short duration ($\lesssim 30$ Myr), cavities move beyond the cooling radius and deposit their energy further from the center than is required if heating is to offset cooling.
2. Entrainment of cool gas by the jet is an important process, as is turbulent mixing of jet-heated and ambient gas.
3. A turbulent vortex that contains a significant quantity of cool gas trails each cavity. After the jet has switched off, the advance of the cavity slows and the vortex overtakes it. When it is about twice as old as the duration of the outburst, the cavity becomes an overdensity.
4. The overdensity overshoots the radius in the cooling flow at which the ambient medium has the same specific entropy. Then it falls back and excites the strong internal gravity waves in the cooling flow that accompany its azimuthal spread and disappearance.
5. Interactions between AGN outbursts are very important. If an outburst follows the last sooner than ~ 70 Myr, the new jet is disrupted at small radii by the turbulent wake of its predecessor and no new cavity forms.
6. Sheets of cold dense gas on the leading edges of cavities, similar to those observed as X-ray bright rims, frequently form as a cavity is driven up through

cold gas that is rising in the wake of the previous cavity.

5. A Statistical Steady State?

The traditional view is that cooling flows are in steady states, with cooling balanced by mass-dropout, but a statistical steady state could be achieved by a sequence of small outbursts by the AGN (Tabor & Binney 1993). A radically alternative point of view is that cooling flows experience a series of cooling catastrophes that provoke powerful AGN outbursts, which rapidly inflate the core of the cooling flow to a significant extent, setting the scene for a prolonged drift towards the next cooling catastrophe (Binney & Tabor 1995; Ciotti & Ostriker 1997, 2001; Kaiser & Binney 2003a). Simulations of the impact of FR II sources on cooling flows (Reynolds et al. 2002; Basson & Alexander 2003) imply that powerful AGN outbursts of the type we observe locally do not heat cluster cores sufficiently to ensure a long interval before the next catastrophe. Less strongly collimated outbursts may achieve longer intervals between catastrophes, but currently a succession of weak outbursts seems the most likely possibility. Moreover, recent observations of X-ray cavities support this conclusion.

If we model the energy density within a cavity by that of a non-relativistic gas, then the *minimum* work done by an AGN in blowing a cavity of volume V in a medium of pressure P is $\frac{5}{2}PV$, of which three fifths resides in the cavity. If the fluid within the cavity is relativistic, the minimum energy is $4PV$. Since the inflation of cavities is likely to be highly irreversible, especially in its early stages and from the perspective of the ambient medium, the actual work done will be larger. Below I shall rather conservatively assume that the work done is $3PV$. Churazov et al. (2003) discuss the physics of cavity inflation in some detail. As a cavity is blown, energy is carried away into the ambient medium by hydrodynamical motions, the high-frequency tail of which will be recognized as non-linear sound waves. Such waves may recently have been observed by Fabian et al. (2003a) in X-ray images of the Perseus cluster. The bulk motions associated with lower frequencies may manifest themselves in the peculiar velocities of H α filaments (Heckman et al. 1989). Much of the energy acquired by ambient gas as a cavity inflates will be used to lift gas up in the cluster potential. The cooling time of the gas will be increased but the gas may not actually heat (Alexander 2002).

Values for the product PV , the X-ray luminosity of the cooling flow L_X (mostly from the classic \dot{M} value) and the characteristic time $\tau = 3PV/L_X$ are given in Table 1. We see that heating associated with cavities can offset radiation from the cooling flow provided outbursts occur every 30 to 120 Myr. Simulations show that cavities rise at of order the sound speed $\sim 1000 \text{ km s}^{-1}$, so they move through $\sim 50 \text{ kpc}$ in 50 Myr. Given the high frequency with which cavities are found in the cores of cooling flows, it is clear that a new pair must be created every $\lesssim 100 \text{ Myr}$. Arguments from synchrotron aging have long implied that more powerful radio sources have lifetimes of this order (Pedlar et al. 1990), but here the

conclusion is slightly different: individual AGN outbursts might last a significantly shorter time than 100 Myr, but the interval *between* outbursts is of this order.

The bottom line of this discussion is that, in a statistical sense, heating by AGN may well balance radiative cooling, as Tabor & Binney (1993) originally conjectured. However, the issue cannot be regarded as closed because as Burns (this meeting) and Thomas (this meeting) have pointed out, cosmological simulations imply that clusters are accreting relatively cool gas. The power required to heat this infalling gas to the virial temperature will significantly increase the power an AGN has to provide if it is to keep its cooling flow in a steady state. The big uncertainty here is how much of the infalling gas reaches the clusters radiatively cooling core. Gas that ends up outside the core can be largely ignored.

6. Conclusions

The *Chandra* and *XMM-Newton* missions have opened the way a clear understanding of how cooling flows work. Distributed mass dropout has been decisively rejected and the importance of heating by AGN established. The data seem to show that there is approximate balance between AGN heating and radiative cooling. Although the heating does have to be episodic, the time between heating episodes is significantly shorter than even the central cooling time, so the radial density profiles of systems do not change greatly around a cooling/heating cycle.

The favored heating agent is collimated outflow from the AGN: a collimated outflow can heat ambient material at several radii and values of specific entropy simultaneously. Consequently there is no need for the system to develop a constant-entropy convective core. It is probably also important for the stability of a cooling flow that it is heated by jets: steepening of the ambient density profile causes the jets to disrupt at smaller radii. The resulting increase in the concentration of the heat source may well be successful in counteracting the increase in the concentration of the cooling rate that accompanies a steepening of the density profile.

Much of the energy in the heating outflow will be contained in a sub-relativistic wind. The opening angle of this wind may not be small. At its core there may or may not be relativistic jets. Observations of synchrotron radiation will be largely sensitive to the relativistic jets and their fall-out, so such observations may provide a very incomplete picture of the overall AGN/cooling flow interaction.

Many questions remain open. Two of the most interesting, and possibly connected, issues are the roles of cosmic infall and cool filaments. Have the filaments formed through condensation of X-ray emitting gas, as has traditionally been argued (Fabian & Nulsen 1977)? If this conjecture were correct, and in view of the thermal stability of gravitationally stratified plasma, it is surprising that the filaments seem so far from dynamical equilibrium: one would expect condensation to occur onto a rotationally supported disk rather than often radially directed filaments. Also, as Sparks et al. (1989) have stressed, one would not expect gas that had condensed from the X-ray emitting plasma to have dust that is simi-

TABLE 1. PARAMETERS FOR FIVE CLUSTERS WITH CAVITIES.

System	$PV/10^{58}$ erg	$L_X/10^{43}$ erg s $^{-1}$	τ /Myr	Reference
Hydra A	27	30	88	McNamara et al. (2000); Nulsen et al. (2002)
A2052	4	3.2	122	Blanton et al. (2001)
Perseus	8	27	29	Fabian et al. (2000); Allen et al. (1992)
A2597	3.1	3.8	79	McNamara et al. (2001)
A4059	22	18	119	Huang & Sarazin (1998); Heinz et al. (2002)

lar to Galactic dust. Perhaps filaments reflect the cosmic infall of cool gas and gas-rich galaxies. Very near the center of the cluster this gas might take so long to evaporate that it can be lighted up by internal star formation and then be observed (Nipoti & Binney in preparation). In this case, the AGN would not normally be accreting gas from filaments, but feeding directly on the X-ray emitting gas. The AGN's luminosity would then be closely con-

nected to the temperature of the coolest X-ray emitting gas, and the efficient operation of thermostatic feedback would be natural and fairly well modeled by equation (2).

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