Structural stability of cooling flows

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Received ...; accepted ...

ABSTRACT
Three-dimensional hydrodynamical simulations are used to investigate the structural stability of cooling flows that are episodically heated by jets from a central AGN. The radial profile of energy deposition is controlled by (a) the power of the jets, and (b) the pre-outburst density profile. A delay in the ignition of the jets causes more powerful jets to impact on a more centrally concentrated medium. The net effect is a sufficient increase in the central concentration of energy deposition to cause the post-outburst density profile to be less centrally concentrated than that of an identical cluster in which the outburst happened earlier and was weaker. These results suggest that the density profiles of cooling flows oscillate around an attracting profile, thus explaining why cooling flows are observed to have similar density profiles. The possibility is raised that powerful FR II systems are ones in which this feedback mechanism has broken down and a runaway growth of the source parameters has occurred.

Key words: cooling flows – X-rays: galaxies: clusters – galaxies: jets – hydrodynamics

1 INTRODUCTION
Data from the Chandra and XMM-Newton X-ray observatories have established beyond reasonable doubt that radio sources associated with the central black holes of X-ray emitting clusters are heating the surrounding ‘cooling flows’ at rates comparable to the radiative cooling rate from within the cooling radius (where the cooling time is equal to the Hubble time). The key observation is that several clusters contain pairs of ‘cavities’ – regions of depressed X-ray surface brightness that in some cases coincide with regions of enhanced brightness in the radio continuum (Bohringer et al. 1993; Churazov et al. 2000; McNamara et al. 2001; Blanton et al. 2001). It is clear that the observed radio jets are inflating pairs of cavities in the thermal X-ray emitting plasma, and that synchrotron emission from the cavities accounts for the enhanced radio-frequency brightness.

Once a cavity is created, it must rise buoyantly (Gull & Northover 1973; Churazov et al. 2001; Quilis et al. 2001; Brüggen & Kaiser 2002; Brüggen et al. 2002), and it may rise even faster if it is endowed at birth with significant momentum as well as energy (Omma et al. 2004). Simulations of cavity dynamics all affirm that cavities rise at speeds comparable to the sound speed in the X-ray emitting gas, $\sim 1000\, \text{km}\,\text{s}^{-1}$ in a typical cluster. In Perseus (Fabian et al. 2001), Abel 2597 (McNamara et al. 2001) and Abel 4059 (Heinz et al. 2002) more than one pair of cavities is detected. The distance from the cluster centre of the outer cavities, combined with the speed at which cavities rise, yields an estimate $\tau \sim 50\,\text{Myr}$ of the time between successive episodes of cavity inflation.

The crudest estimate of the energy injected during cavity inflation is $\frac{1}{2}PV$ if the plasma in the cavity is subrelativistic, or $4PV$ in the contrary case. Since cavities must be irreversibly inflated, these estimates for reversible inflation are underestimates. Binney (2003) gives estimates for five clusters of the ratio $\tau$ of the estimate $3PV$ of the energy injected during the inflation of observed cavities to the X-ray luminosity. The values of $\tau$, which are significantly uncertain, range from 30 Myr to 120 Myr, implying that an outburst needs to occur each 50 to 100 Myr to maintain a balance between radiative losses and heating by the radio source. It is striking that this estimate of $\tau$ from the hypothesis that heating balances cooling coincides to within the uncertainties with the direct estimate of $\tau$ yielded by clusters with two pairs of cavities. Arguments from synchrotron aging have long implied that more powerful radio sources have lifetimes of the order 100 Myr (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.

It is to be expected that a drop in the central temperature of cooling-flow gas will increase the accretion rate of the embedded black hole, and thus the rate at which the radio source heats the flow (Tabor & Binney 1993). Consequently, the possibility exists for a steady-state balance between heating and cooling, such as occurs in the cores of main-sequence stars. However, there are many observational indications that the luminosities of radio sources are
unsteady – for example the existence of cavities and of powerful FR II radio galaxies, which in 100 Myr can pump as much energy into the intracluster medium as it can radiate in a Hubble time. We need a better understanding of the cause and extent of this unsteadiness.

Another area in which we urgently need a better understanding is in the radial distribution of heat input by the radio source. Tabor & Binney (1993) assumed that heat was applied at very small radii, leading to the development of an adiabatic core. Recent X-ray data show that the specific entropy decreases inwards to the smallest radii probed (Kaiser & Binney 2003). Such a situation arises naturally when the radio source heats the X-ray gas with a collimated outflow, because heating then occurs where the outflow energy thermalizes, which is expected to extend over a significant range in radius (Binney & Tabor 1995).

The radial distribution of energy input by the radio source depends on two factors: (i) the power and degree of collimation of the outflow, and (ii) the radial density profile of the intracluster gas. The more powerful and better collimated the outflow is, the further out it will go before it disrupts. Hence powerful, strongly collimated outflows, such as those of FR II radio galaxies, deposit most of their energy at large radii, and probably outside the cooling radius (Reynolds et al. 2001, 2002, Basson & Alexandre 2003). The more steeply the density of the X-ray gas increases towards the cluster centre, the more readily the gas can disrupt a given jet, and thus the more centrally concentrated the energy injected into the ICM will be.

These considerations raise a question about the stability of cooling flows. Consider two initially identical cooling flows that are both experiencing periods of nuclear quiescence. In flow 1 the radio source switches on at time $t_1$, while that in flow 2 switches on at a later time $t_2$. On account of the additional period $t_2 - t_1$ of cooling experienced by flow 2, the jet in this system will impact on a more centrally concentrated distribution of gas than that impacted by the jet of flow 1. On the other hand, if heating and cooling are to be in statistical balance in both flows, the luminosity of the jet in flow 2 must be larger than that in flow 1. This greater luminosity will tend to make the energy deposition less centrally concentrated.

If the effect on the radial distribution of energy input from enhanced luminosity is greater than that from increased central concentration of the X-ray gas, the post-outburst density profile of flow 2 will be more concentrated than that of flow 1. A runaway situation will then arise, in which ever more powerful outbursts, driven by a steadily rising central gas density, deposit their energy at larger and larger radii. FR II sources might be the cataclysmic end points of such a runaway.

In the contrary case, the dominating factor is the tendency of the steeper density profile of the pre-outburst gas to concentrate injected energy at small radii, and in flow 2 the post-outburst gas is no more centrally concentrated than that in flow 1. In this case the density profiles of both flows will tend to fluctuate around some stable density profile of the X-ray emitting gas. The fact that many cooling flows have density profiles that differ mainly in an overall scaling, even though their central cooling times are of order a thirty-fifth of the Hubble time, suggests that there is a significant range of parameters in which such stability is possible.

### Table 1. Parameters of the simulations

| Simulation | $\dot{m}_{\text{jet}}$ ($M_\odot$ yr$^{-1}$) | $v_{\text{jet}}$ ($10^3$ km s$^{-1}$) | $P_{\text{jet}}$ ($10^{44}$ erg s$^{-1}$) | $\Delta t$ (Myr) | $\Delta E$ ($10^{59}$ erg) |
|------------|------------------------------------------|----------------------------------|----------------------------------|-----------------|------------------|
| S1         | 1                                        | 28                               | 5                                | 25              | 4                |
| S2         | 1                                        | 30                               | 10                               | 25              | 8                |
| S3         | 1                                        | 28                               | 5                                | 50              | 8                |
| S4         | 1                                        | 28                               | 5                                | $2 \times 25$   | 8                |
| S5         | 1                                        | 40                               | 10                               | 25              | 8                |

In this paper we use simulations to investigate the existence of such a stable configuration.

### 2 THE SIMULATIONS

We have used the Eulerian hydrocode ENZO (Bryan & Norman 1997; Bryan 1999) to make a suite of five simulations of cooling-flow evolution. The simulations are fully three-dimensional and use an adaptive mesh to achieve an effective (maximum) resolution of 0.61 kpc. The simulations employ the PPM Riemann solver (Colella & Woodward 1984). The computational volume is a box 628 kpc on a side, with periodic boundary conditions. The twin jets were imposed by the algorithm described in Omma et al. (2004). Table 1 lists the parameters of the simulations. The quantities $\dot{m}_{\text{jet}}$, $v_{\text{jet}}$ and $P_{\text{jet}}$ quantify the rate at which mass, momentum and energy are injected at the base of the jet through the formulae $p = \dot{m}_{\text{jet}}v_{\text{jet}}$ and $P_{\text{jet}} = \frac{1}{2}\dot{m}_{\text{jet}}v_{\text{jet}}^2$.

The initial conditions are for gas in hydrostatic equilibrium in an NFW (Navarro, Frenk & White 1997) gravitational potential. The gas cools radiatively throughout the simulation. The central cooling time is initially 380 Myr, so cooling steepens the density profile quite rapidly. After 250 Myr each simulation has a distinctly cooled, high-density core.

In Simulation 1 the jets fire after 262 Myr of cooling. They have a total power of $5 \times 10^{59}$ erg s$^{-1}$ and run for 25 Myr, during which time they inject $4 \times 10^{59}$ erg. The jets in Simulations 2 to 4 fire after 300 Myr of cooling, by which time an extra $4 \times 10^{59}$ erg has been lost to radiation, and they inject $8 \times 10^{59}$ erg. Thus the later ignition of the jets in Simulations 2 to 4 is compensated for by enhanced energy injection.

Simulations 2 to 4 differ in the pattern of their outbursts. The jets in Simulation 2 are twice as powerful as those in Simulation 1 and run for the same time (25 Myr). The jets in Simulation 3 have the same power as those in Simulation 1 but fire for twice as long (50 Myr). The jets in Simulation 4 have the same power but fire for two 25 Myr intervals, separated by a quiescent interlude 25 Myr long.

In Simulation 5 the jets fire at the same early time as in Simulation 1, but with the power level and duration that are characteristic of Simulation 2.

In Fig. 1 the dotted curve shows the density profile of the cluster gas at the start of all simulations. The data points show the density in the Hydra cluster as deduced by David et al. (2000). The full curve labelled $t = 0$ shows the density profile at the ignition of the jets in Simulations 1 and 5, while the dashed curve labelled $t = 0$ shows the density profile at the ignition of the jets in Simulations 2 to 4.

### Table 1. Parameters of the simulations
4. The effect on the density profile of $\sim 300\text{ Myr}$ of passive cooling is evident. The bottom full curve shows the spherically averaged density profiles $42\text{ Myr}$ after the firing of the jet in Simulation 1, while the bottom dashed curve shows the same data for Simulation 2. At that time, $17\text{ Myr}$ after the jets extinguished, the curves are quite similar to the initial profile and the data. Thus in both simulations the injected energy has effectively reversed the effect of $300\text{ Myr}$ of cooling.

Most crucially, the dashed curve of Simulation 2 now lies below the full curve, implying that the system that cools for longer and has the most centrally concentrated density when its jets ignite, ends up with the less centrally concentrated profile. The density profiles at times later than those shown in Fig. 1 confirm that the greater central concentration of Simulation 1 at $t = 42\text{ Myr}$ is not an aberration: the profile for Simulation 1 remains on top of that of Simulation 2, and moves upwards faster. Consequently, when the profiles are next similar to those labelled $t = 0$ in Fig. 1, we can expect Simulation 1 to be the scene of the more energetic outburst slamming into the more centrally concentrated ICM. When the dust settles after this second outburst, the profile of Simulation 2 will be the more centrally concentrated and the pair of simulations will have come full cycle. Hence these simulations strongly support the proposition that the density profiles of cooling-flow clusters oscillate around an attracting profile.

Simulations 3 to 5 probe the sensitivity of a cooling flow’s response to the temporal pattern of energy injection. In Fig. 2 the light curves show the temperature profiles just before jet ignition: the full curve applies to simulations 1 and 5 that experience early ignition, while the dashed curve applies to Simulations 2 to 4. The full curves show the spherically averaged temperature profiles $120\text{ Myr}$ after jet ignition. Contrast, at the centre the heavy dashed curve of Simulation 2 lies distinctly above the curves for Simulations 1 and 5. Since the jets in Simulations 2 and 5 are identical in power and duration, the higher central temperature of Simulation 2 at $120\text{ Myr}$ must be due to the injected energy being concentrated in the centre by the more centrally concentrated pre-ignition density profile.

Fig. 2 shows that the weaker, longer-lasting jets of Simulations 3 (long-dashed curve) and 4 (dash-dot curve) produce higher central temperatures than the short-lived powerful jets of Simulation 2. Thus energy injected by a weaker jet is more centrally concentrated than energy injected by a stronger jet since in a given intracluster medium a weaker jet will disrupt at a smaller radius. Another relevant factor is revealed by examination of plots of specific entropy: in part jets heat the core by entraining and carrying upward some of the coldest gas. In Simulation 2 much of what is initially lifted out of the core falls straight back after the jets have died. The weaker but longer lasting jets of Simulation 3, carry cold material further out, thus reducing the amount that falls back.

It is interesting that Simulation 3 with a single sustained $50\text{ Myr}$ blast yields a higher central temperature than Simulation 4 with two blasts of $25\text{ Myr}$ duration. Two factors seem to contribute to this phenomenon. First, after a burst lasting only $25\text{ Myr}$ much of the entrained cold material falls straight back. Second, the later blast in Simulation 4 has little difficulty in linking up with the cavity blown by the first blast, which continued to move outwards over the $25\text{ Myr}$ of quiescence between the blasts. Consequently, the radii at which most of the cavity’s energy is deposited are larger than the radii heated by the second half of the sustained blast in Simulation 3. That is, a $25\text{ Myr}$ period of quiescence is not long enough to make two blasts independent of one another.

3 CONCLUSIONS

A suite of three-dimension hydrodynamical simulations of the reheating of intracluster gas by jets has been used to
investigate the structural stability of cooling flows that are episodically reheated by jets.

During a period of quiescence by the AGN, radiative cooling rapidly increases the central concentration of the ICM. At some point the rising central density of the ICM is expected to provoke an outburst by the AGN. The precise instant at which the outburst comes is likely to vary from outburst to outburst, and be correlated with the outburst’s strength in the sense that later outbursts that are fed by a more centrally concentrated ICM are likely to be more powerful. The more powerful a jet is, the further out it deposits its energy.

Simulations in which the time of the outburst is varied along with the strength and/or duration of the outburst, suggest that cooling flows have a tendency to structural stability in the following sense. On occasions when there is an unusually long period of quiescence by the AGN and passive cooling makes the intracluster gas unusually centrally concentrated immediately before an outburst by the AGN, a larger fraction of the AGN’s energy is dissipated at small radii because, notwithstanding the increased power or duration of the outburst, the jets are disrupted near the AGN by the unusually dense ICM. Moreover, entrainment of cold gas by the jets is an important mode of core heating, and the denser ICM increases the mass of cold gas that is entrained.

Hence these simulations provide a framework for understanding why the density profiles of cooling flows do not span a wide range.

Integration of FR II sources into this framework is an important task for the future. There is a tantalizing possibility that these intrinsically rare sources are ones in which the stabilizing feedback loop that we have described has broken down: above some critical power, too little energy is deposited in the immediate vicinity of the black hole to throttle accretion onto the hole, and a runaway growth in accretion rate, jet power and physical source size may ensue. Both observations and simulations indicate that powerful FR II sources deposit nearly all their energy outside the cooling radius. Heating the ICM at such large radii can have little impact on the black hole’s accretion rate. Unfortunately, it is hard for simulations to determine accurately what small fraction of a large FR II power is dissipated near the centre, where the hole’s accretion rate is determined. The computational problem is akin to that involved in simulating a core-collapse supernova, since here again an extremely small fraction of a large energy budget is responsible for driving matter away from the collapsing core.

It is worth noting that, at a given power, a narrower jet will deposit a smaller fraction of its energy in the core because it will entrain less cold gas. Hence FR II sources may be characterized by unusually narrow jets.

The existence of an effective feedback loop in cooling flows is easier to understand if the black hole accretes directly from the hot ICM rather than from an accretion disk fed with gas that has cooled catastrophically to $< 10^5$ K. It is well known that the Bondi-Hoyle accretion rates of black holes at the centres of cooling flows are more than sufficient to power the cooling flow [Fabian & Canizares 1988]. Moreover, the connection between radio sources is well established [Krolik 1998]. This as yet unexplained connection would make sense if energy released by accretion of hot gas is channelled into jets rather than radiation, because elliptical galaxies are, almost by definition, systems in which the interstellar medium is at the virial temperature, rather than made up of cold, centrifugally supported gas. If the black holes in cooling flows do indeed feed off virial-temperature gas, it follows that AGN effectively prevent cooling of virial-temperature gas. This conclusion has radical implications for the theory of galaxy formation and the origin of the galaxy luminosity function [Binney 2004]. It also implies that the filaments of cold gas that have been observed in several systems must be gas that fell in cold [Sparks et al. 1985; Nipoti & Binney 2004] rather than gas that has cooled from the X-ray emitting phase.

**REFERENCES**

Basson J.F., Alexander P., 2003, MNRAS, 339, 353
Binney J., 2003, In “The Riddle of Cooling Flows in Galaxies and Clusters of Galaxies”, ed. T.H. Reiprich, J.C. Kempner & N. Soker (astro-ph/0310222)
Binney J., 2004, MNRAS in press (astro-ph/0308172).
Binney J., Tabor G., 1995, MNRAS, 276, 663
Blanton E.L., Sarazin C.L., McNamara B.R., Wise M.W., 2001, ApJ, 558, L15
Böhringer H., Voges W., Fabian A.C., Edge A.C., Neumann D.M., 1993, MNRAS, 264, L25
Brüggen M., Kaiser C.R., 2001, MNRAS, 325, 676
Brüggen M., Kaiser C.R., 2002, Nature 418, 301
Brüggen M., Kaiser C.R., Churazov E., Emslin T.A., 2002, MNRAS 331, 545
Bryan G.L. 1999, Computing in Science and Engineering, 1:2, 46
Bryan G.L., Norman M.L., 1997, in ‘Computational Astrophysics’, ASP Conf. Ser. 123, p. 363
Churazov E., Brüggen M., Kaiser C.R., Böhringer H., Forman W., 2001, ApJ, 554, 261
Churazov E., Forman W., Jones C., Böhringer H., 2000, A&A, 356, 788
Colella P., Woodward P.R., 1984, J. Comp. Phys., 54, 174
David L.P., Nulsen P.E.J., McNamara B.R., Forman W., Jones C., Ponnan T. Robertson B., Wise M., 2001, ApJ, 557, 546
Fabian A.C., Canizares, C., 1988, Nature, 333, 829
Fabian A.C. et al., 2000, MNRAS, 318, L65
Gull S.F., Northover K.J.E., 1973, Nature, 244, 80
Heinz S., Choi Y.-Y., Reynolds C.S., Begelman, M.C., 2002, ApJ, 569, L79
Kaiser C.R., Binney J., 2003, MNRAS, 338, 837
Krolik J.H., 1998, ‘Active Galactic Nuclei’, Princeton: Princeton University Press
McNamara B., Wise M., Nulsen P.E.J., David L.P, Sarazin C.L., Bautz M., Markevitch M., Vikhlinin A., Forman W.R., Jones C., Harris D.E., 2000, ApJ, 534, L135
McNamara B. et al, 2001, ApJ, 562, L149
Navarro J.F., Frenk C.S., White S.D.M., 1997, ApJ, 490, 493
Nipoti C., Binney J., 2004, MNRAS, submitted
Omma H., Binney J., Bryan G., Slyz A., 2004, MNRAS in press (astro-ph/0307471)
Pedlar A., Chataway H.S., Davies R.D., Harrison B.A., Perley R., Crane P.C., Unger S.W., 1990, MNRAS, 246, 477
Quilis V., Bower R.G., Balogh M.L., 2001, MNRAS, 328, 1091
Reynolds C.S., Heinz S., Begelman M.C., 2001, ApJ, 549, L179
Reynolds C.S., Heinz S., Begelman M.C., 2002, MNRAS, 332, 271
Sparks W.B., Macchetto F., Golombek D., 1989, ApJ, 345, 153
Tabor G., Binney J., 1993, MNRAS, 263, 323