AGN Heating through Cavities and Shocks

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1 Introduction

The X-ray emitting gas with cooling times much shorter than the Hubble time in elliptical galaxies, and at the centers of groups and clusters of galaxies is in an unstable state. If it is heated at a mean rate much less than the power it radiates, much of it would cool quickly to low temperatures, forming reservoirs of cold gas and young stars well in excess of those that are observed, e.g. [1, 2, 3]. If the gas is heated at a rate significantly exceeding the power it radiates, its cooling time would increase until it became comparable to the Hubble time or longer. Thus, the relatively high incidence of short central cooling times requires that the gas is heated at a mean rate closely matching the power it radiates. This is difficult to explain, unless heating rates are coupled to cooling rates. AGN heating is a natural vehicle to provide the coupling [4].

It has been established that the energy released by AGN at the centers of cooling flows is sufficient to have a significant impact on the cooling gas [5, 2]. Not only are the energies from AGN outbursts comparable to those needed to stop the gas from cooling, but the mean powers of the outbursts are well correlated with the powers radiated. While the heating process is not well understood, this would be a remarkable coincidence if AGN heating does not play a significant role in preventing the gas from cooling.

Three comments on AGN heating of cooling flows are made here. First, a simple physical argument is used to show that the enthalpy of a buoyant radio lobe is converted to heat in its wake. Thus, a significant part of “cavity” enthalpy is likely to end up as heat. Second, the properties of the repeated weak shocks in M87 are used to show that they can plausibly prevent gas close to the AGN from cooling. As the most significant heating mechanism at work closest to the AGN, shock heating probably plays a critical role in the feedback mechanism. Finally, results are presented from a survey of AGN heating rates in nearby giant elliptical galaxies. With inactive systems included, the overall AGN heating rate is reasonably well matched to the total
cooling rate for the sample. Thus, intermittent AGN outbursts are energetically capable of preventing the hot atmospheres of these galaxies from cooling and forming stars.

2 Cavity Heating

X-ray decrements over radio lobes are generally consistent with the lobes being devoid of hot gas, e.g. [6], so we treat them as massless. From the perspective of the ICM, a cavity (lobe) rises because ICM falls inward around it to fill the space it occupies (Fig. 1). This converts gravitational potential energy to kinetic energy in the gas flow around the rising cavity. Details of the flow depend on the viscosity, which is poorly determined. If it is high, the flow is laminar and the kinetic energy is dissipated as heat over a region comparable in size to the cavity (akin to Stoke’s flow around a sphere [7]). If the viscosity is very low, the Reynolds number would be high and the flow turbulent. The turbulent region near the cavity would have a similar size to it. Turbulent kinetic energy is dissipated in the turn over time of the largest eddies [7], so that the dissipation time \( t_d \sim r_{cav}/v_{cav} \), where \( r_{cav} \) is the radius of the cavity and \( v_{cav} \) is the speed of the eddy, which is comparable to the speed of the cavity. Since \( t_d v_{cav} \approx r_{cav} \), much of the turbulent kinetic energy is dissipated in a region of comparable size to the cavity. Thus, regardless of the viscosity, the kinetic energy created by cavity motion is dissipated locally as heat in a wake of similar size to the cavity.

The gravitational potential energy that is released as the cavity rises a small distance \( dR \), subject to the gravitational acceleration \( g \) is (Fig. 1)

\[
M g \, dR = V \rho g \, dR \approx -V \frac{dp}{dR} \, dR = -V \, dp, \tag{1}
\]

where \( M = \rho V \) is the mass of gas displaced by the cavity, \( V \) is the volume of the cavity and \( \rho \) is the density of the external gas. Cavity motion is generally subsonic, so that the gas around the cavity is approximately hydrostatic, i.e.,
$\rho g \simeq -dp/dR$. The final $dp$ here is the pressure change in the external gas over the distance $dR$, but a subsonic cavity maintains approximate local pressure equilibrium, so that $dp$ may also be regarded as the change in pressure of the cavity. In terms of the enthalpy, $H = E + pV$, the first law of thermodynamics, $dE = TdS - p dV$, becomes $dH = TdS + Vdp$. In an adiabatic process, the heat exchange, $TdS$, is zero and $dH = Vdp$. Thus, equation (1) states that the potential energy released as the cavity rises is equal to the decrease in its enthalpy. No exotic process is required to explain how cavity enthalpy is converted to heat. This argument is less accurate for the largest cavities (with $r_{\text{cav}} \simeq R$), but the corrections are of order unity. Fragmentation of cavities does not change the result, unless cavity contents dissipate. We conclude that enthalpy lost by rising cavities is dissipated as heat locally in their wakes [5].

3 Weak Shock Heating

Weak shocks associated with AGN outbursts are generally only detected in deep X-ray observations, so that relatively few are known, e.g. [8, 9, 10, 11, 12], although they are probably produced in most AGN outbursts. The energies required to drive the shocks are comparable to cavity enthalpies, but much of this energy will end up as potential energy in the ICM. The main requirement for stopping gas from cooling is to replace the entropy lost by radiation and, since the entropy jump, $\Delta S$, varies as the cube of the pressure jump, weak shocks are not very effective at this [13]. The equivalent heat input per unit mass can be evaluated as

$$\Delta Q \simeq T \Delta S = E \Delta \ln \frac{p}{\rho^\gamma},$$

(2)

where $E$ is the specific thermal energy, $p$ the pressure and $\rho$ the density of the gas. Thus, the fractional heat input, $\Delta Q/E$, is given by the jump of $\ln p/\rho^\gamma$ in the shock.

Three weak shocks are visible in the X-ray image of M87 [14]. Fitting a simple model to the surface brightness profile of the innermost shock at 0.8 arcmin ($\simeq 3.7$ kpc) gives a Mach number of $\simeq 1.4$ and a shock age of $\simeq 2.4 \times 10^6$ y. Its equivalent heat input (equation 2), determined from the Mach number, is $\Delta Q/E \simeq 0.022$. Clearly, this single shock does very little to heat the gas. However, there is a second shock at about twice the radius, and the third shock, at $\simeq 3$ arcmin, required several times more energy [8]. Thus, a shock of comparable strength to the 0.8 arcmin shock may well occur every $\sim 2.5 \times 10^6$ y. The cooling time of the gas at 0.8 arcmin $\simeq 2.5 \times 10^6$ y, so that there is time for $\sim 100$ such shocks during the cooling time. Therefore, the combined heat input of the shocks ($100 \times 0.022 = 2.2$) is more than enough to make up for radiative losses from the gas.

These numbers are not to be taken literally, but they make a plausible case that the modest heating of repeated weak shocks can stop the gas at 0.8
arcm in from the AGN in M87 from cooling. The cavity heating discussed in section 2 is only effective beyond the radius where the radio lobes form. Some other mechanism is required to prevent gas closer to the AGN from cooling. Since the gas closest to the AGN is likely to be its most significant source of fuel, the heating process that affects this gas probably plays a critical role in the feedback cycle that prevents gas from cooling. Thus, while weak shock heating is unlikely to be the dominant mode [15], it may well play a major role in the AGN feedback process.

4 AGN Heating in Nearby Elliptical Galaxies

![Cavity heating power vs cooling power for nearby elliptical galaxies. Heating powers, $P_{cav}$, are estimated as $pV/t_a$, using three different estimates of the age, $t_a$, for the 27 galaxies with cavities in the sample of Jones et al.. Cooling power is the X-ray luminosity from within the projected radius where the cooling time equals $7.7 \times 10^9$ y. The dashed lines show where heating power equals cooling power, for heat inputs per cavity of $pV$, $4pV$ and $16pV$, from top to bottom.]

To date, deeper X-ray observations of clusters have almost invariably revealed more cavities, e.g. [14], so that heating powers are likely to be underestimated from existing data [5, 2]. Progress in this area is also hampered by relatively poor understanding of the selection effects for finding cavities [5]. A deep survey of a complete sample of cooling flow clusters is required to assess the overall significance of AGN heating in clusters. In the mean time, Jones et al. (in preparation and this proceedings) have assembled X-ray observations of a nearly complete sample of nearby giant elliptical galaxies. This includes $\approx 160$ galaxies, 109 of which show significant diffuse emission from
hot gas after removal of resolved and unresolved point sources. Of those, 27 have significant AGN cavities. The sample is used here to assess the overall significance of AGN heating.

Our determinations of AGN heating rate parallel those of Birzan et al. [5] and Rafferty et al. [2], with minor modifications. Where gas temperatures are not available from the literature, they are estimated from the velocity dispersion, $\sigma$, of a galaxy as $kT = 1.5\mu m_H\sigma^2$ (consistent with the median of $\mu m_H\sigma^2/(kT)$ for the remaining galaxies). For the three galaxies without a temperature or velocity dispersion, the gas temperature is set to the median value of 0.7 keV. Abundances are assumed to be 0.5 solar. Electron densities are determined from beta model fits. Heating powers are estimated as $pV$ per cavity, divided by one of the three estimates of cavity age, the sound crossing time, the buoyant rise time, or the refill time [5]. The cooling power is taken as the X-ray luminosity from within the projected radius where the cooling time equals $7.7 \times 10^9$ y. Our cooling powers are not corrected for mass deposition, cf. [5, 2].

The three resulting estimates of heating power are plotted against the cooling power in Fig. 2. Note that for UGC 408, the AGN appears to lie near the center of a single cavity, suggesting that the system is viewed almost along its radio axis, with its cavities and AGN projected on top of one another. The apparent distance from the AGN to the center of the cavity is then much smaller than the real distance, causing the age of the outburst to be underestimated and the heating power to be overestimated. Consistent with this, the naive estimates of its heating power are exceptionally high. For UGC 408 alone, we have therefore assumed that the distance from the center of the cavity to the AGN is equal to the semimajor axis of its cavity. The corrected heating powers agree with those for other systems with similar cooling powers. This correction reduces our estimate of the total heating power for all systems by a factor of $\sim 2$.

Approximately half of the outbursts in cooling flow clusters have heating powers that match or exceed their cooling powers for a heat input of $4pV$ per cavity [2]. By contrast, this is true for all of the nearby giant ellipticals in our sample (Fig. 2), apart from NGC 1553 [17]. Conversely, only about one quarter of the giant ellipticals with significant emission from hot gas have cavities, whereas the fraction of cluster cooling flows with outbursts is closer to 70% [16]. Consistent with the AGN feedback model, this suggests that the duty cycles of outbursts in larger systems have to be greater to keep the mean heating power at the level needed to stop cooling.

Allowing $1pV$ per cavity, the total heating powers for the 27 systems are $2.6 \times 10^{43}$, $2.9 \times 10^{43}$ and $1.5 \times 10^{43}$ erg s$^{-1}$, corresponding to ages of the sound crossing times, the buoyant rise times and the refill times, respectively. The total cooling power for all 109 galaxies with significant emission from diffuse hot gas is $1.06 \times 10^{44}$ erg s$^{-1}$, so that the ratios of total cooling power to total heating power for the three age estimates are 4.1, 3.6 and 6.9, in turn.
The enthalpy of a cavity dominated by relativistic gas is $4pV$ and this value might, typically, be doubled by the “shock energy” (more precisely, the $pdV$ done as the cavity was inflated). While there is still significant systematic uncertainty in these numbers, they make a good case that AGN outbursts in nearby giant elliptical galaxies can prevent their X-ray emitting gas from cooling and forming stars. The outbursts are intermittent, with the AGN active $\sim 25\%$ of the time.

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