

Interaction of the AGN and X-Ray Emitting Gas

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The process that prevents the deposition of cooled gas in cooling flows must rely on feedback in order to maintain gas with short cooling times, while preventing the bulk of the gas from cooling to low temperatures. The primary candidate for the feedback mechanism is the accretion of cooled and cooling gas by an active galactic nucleus (AGN). Despite some difficulties with this model, the high incidence of central radio sources in cooling flows and the common occurrence of radio lobe cavities, together, support this view. The Bondi accretion rate for the intracluster gas onto the AGN depends on the gas properties only through its specific entropy and that is governed directly by competition between heating and cooling. This provides a viable link for the feedback process. It is argued that the mass accreted between outbursts by the central AGN is only sensitive to the mass of the black hole and the gas temperature. Bondi accretion by an AGN leads to a simple expression for outburst energy that can be tested against observations.

1. Introduction—the Significance of AGN Heating

A variety of mechanisms have been proposed to explain why large quantities of gas do not cool to low temperatures at the centers of cooling flows (many discussed elsewhere in these proceedings). While there are many candidate heating mechanisms, in general, short central cooling times, as little as 10^8 – 10^9 y in many clusters (e.g. David et al. 2001; Takizawa et al. 2003) and an order of magnitude shorter still in elliptical galaxies (e.g. Mathews & Brighenti 2003), are very difficult to maintain without a process involving feedback. In the absence of feedback, any heating process will either overwhelm, or be overwhelmed by radiative cooling in a few cooling times. Adding to this the observation that outbursts from central AGN's have an impact on the the hot gas through the creation of cavities around radio lobes (e.g. McNamara et al. 2000; Fabian et al. 2000; Blanton et al. 2001) in clusters, groups and isolated elliptical galaxies, and the prevalence of radio sources at the centers of cooling flows (Burns 1990), suggests that AGN feedback is the prime candidate as the process that prevents mass deposition in cooling flows.

This is not to dismiss the difficulties faced by the AGN feedback model (e.g. Fabian et al. 2001; Brighenti & Mathews 2003, and elsewhere in these proceedings). However, it has been well demonstrated that a modest amount of thermal conduction could make a significant contribution to the energy budget of the regions in clusters where the cooling time is shorter than the age. Thermal conduction could, therefore, alleviate the major problem of the AGN feedback model in clusters, but as also shown by Zakamska & Narayan (2003), thermal conduction cannot prevent the deposition of cooled gas in all cluster cooling flows. The steep temperature dependence of the thermal conductivity ($\kappa \sim T^{5/2}$) means

that thermal conduction is less effective in groups, and less still in isolated elliptical galaxies. Furthermore, the region in clusters where the cooling time is shorter than the Hubble time is relatively small, so that the remainder of the cluster can act as a thermal reservoir to make up for radiative losses from the center. This is not the case in isolated elliptical galaxies, where radiative losses are significant throughout the system. Thus, while thermal conduction may be important for the energy budget of cluster cooling flows, it is unlikely to have much impact in cooler systems.

For the clusters with radio cavities studied to date, single AGN outbursts have very little impact on the cluster as a whole. However, the opposite is true for isolated elliptical galaxies. This is clear from observations of systems such as M84 (Finoguenov & Jones 2001), where a single radio outburst has disrupted the entire hot interstellar medium of the galaxy. Thus, while there is room to doubt the significance of heating by AGN outbursts in cluster cooling flows, there is a strong case that they can regulate the deposition of cooled gas in elliptical galaxies (but see Brighenti & Mathews 2003). It would be surprising if the mechanism that regulates cooling in the larger systems was fundamentally different.

If AGN feedback is the process that regulates the deposition of cooled gas in cooling flows, then it must be powered by the accretion of cooled and cooling gas onto the AGN. The remainder of my talk is a simpleminded consideration of what we should expect in that case.

2. Bondi Accretion from Cooling Hot Gas

It is well known that angular momentum plays a critical role in accretion onto a black hole, *i.e.* an AGN. Since the ratio of the Bondi radius, where the influence of the black hole on the surrounding gas starts to be significant, to the Schwarzschild radius is roughly $c^2/s^2 \sim 10^5$ – 10^6 , angular momentum that is negligible at the Bondi ra-

dius can have a dominant effect on the subsequent flow. Here it is assumed that accreted gas is fed into a reasonably compact accretion disc, from where it is fed into the AGN. At the least, this means that there need not be a very close link between the Bondi accretion rate and the instantaneous accretion rate onto the AGN. Nevertheless, gas that is fed into the disc is assumed to be available to fuel the AGN. It should also be noted that, based on numerical simulations, Proga & Begelman (2003a,b) have cast considerable doubt on the Bondi accretion formula. Despite this, it is employed here for want of a better replacement. It is unclear from the results of Proga & Begelman (2003b) under what conditions, if any, the Bondi accretion rate may apply. In particular, those simulations are adiabatic and when radiative cooling becomes appreciable at the Bondi radius ($\beta \rightarrow 1$ below) the Bondi result may be more accurate, and the estimate of the accreted mass would still apply.

The ratio of specific heats in the intracluster gas is $\gamma = 5/3$, so that the Bondi accretion rate depends on the gas properties through its entropy alone. The accretion rate from uniform gas with density ρ_0 and temperature T_0 may be expressed as

$$\dot{M}_B = \pi \frac{(GM_h)^2}{\Sigma_0^{3/2}} \simeq 0.012 n_e T^{-3/2} M_9^2 M_\odot \text{ y}^{-1}, \quad (1)$$

where the black hole mass is $M_h = 10^9 M_9 M_\odot$, the entropy is represented by $\Sigma_0 = s_0^2 \rho_0^{-2/3}$, with the sound speed $s_0 = 519 T^{1/2} \text{ km s}^{-1}$, the electron density corresponding to ρ_0 is $n_e \text{ cm}^{-3}$ and T is kT_0 in keV. It should also be noted that for $\gamma = 5/3$ the sonic point in the accretion flow occurs at $R = 0$, and the accretion rate is determined by the entropy of the gas at this point. As a result, the galactic environment has little effect on the Bondi accretion rate (and we can insert the density and temperature at any point in the flow into equation (1) to get the accretion rate).

Radiative cooling directly affects the entropy of the gas, hence the Bondi accretion rate. Expressed in terms of the specific entropy S , the energy equation for the gas may be written

$$\rho T \frac{dS}{dt} = -n_e n_H \Lambda(T), \quad (2)$$

where d/dt is the convective or Lagrangian time derivative. This equation can be rewritten in terms of the entropy proxy, Σ above, as

$$\frac{d \ln \Sigma}{dt} = -\frac{1}{t_{\text{cool}}}, \quad (3)$$

where the radiative cooling time is defined as usual,

$$t_{\text{cool}} = \frac{3\rho kT}{2\mu m_H n_e n_H \Lambda(T)}. \quad (4)$$

This makes the link between cooling and Bondi accretion very clear. Cooling reduces the entropy, as in equation (3), and the entropy determines the Bondi accretion rate, as in equation (1). Any heat input to the gas that results from AGN activity would be added to the right hand side of equation (2), allowing us to close the feedback loop. Of course, the details of this process may be

complex and, in particular, cycles of heating, accretion and cooling may be intermittent rather than steady.

The behavior of cooling gas is relatively simple. Radiative losses reduce the entropy of the gas, which is therefore compressed by surrounding gas in order to maintain hydrostatic equilibrium. This causes inflow. The most counterintuitive feature of this flow is that, as a result of the compression, the temperature of the cooling gas is maintained at about the ‘‘virial temperature’’ of the gravitational potential in which it resides. That is, the gas temperature at radius R is given by $kT(R)/(\mu m_H) \simeq GM(R)/R$ (to within a factor of order unity), where $M(R)$ is the gravitating mass within R (this only fails if the virial temperature decreases too rapidly with decreasing radius).

The primary condition required to maintain the temperature of the cooling gas close to the virial temperature is that the gas must remain approximately hydrostatic. The condition for this is that the cooling time of the gas exceeds its sound crossing time, *i.e.* at radius R , that $t_{\text{cool}} \gtrsim t_{\text{sc}} = R/s$, where s is the speed of sound in the gas. If the cooling time falls below the sound crossing time, the gas will cool to low temperature, more-or-less in place (*i.e.* isochorically), and its subsequent behavior is strongly time-dependent.

For the Bondi accretion flow, what matters is the ratio of cooling time to sound crossing time at about the Bondi radius. Inside the Bondi radius, the ratio of cooling time to sound crossing time increases inward in the Bondi flow ($\propto T/\Lambda(T)$), so that radiative cooling is unimportant throughout if it is unimportant at the Bondi radius. The ratio of cooling time to sound crossing time at the Bondi radius is

$$\beta = \left. \frac{t_{\text{cool}}}{t_{\text{sc}}} \right|_{r_B} \simeq \frac{2kT_0 s_0^3}{\mu n_{e,0} GM_h \Lambda(T_0)} \quad (5)$$

(where we have used $\rho_0/n_{H,0} = 4m_H/3$, as appropriate for gas that is 25 percent helium by mass). Thus, as the gas cools, the temperature of the gas at the Bondi radius remains nearly constant, at about the virial temperature as long as $\beta > 1$. If the cooling time becomes shorter than the sound crossing time at the Bondi radius, then the gas temperature at the Bondi radius will plummet. Formally, this causes a dramatic increase in the Bondi radius and accretion rate, but in practice the flow will become strongly time-dependent. Gas near to the Bondi radius will go into free-fall, and we should expect a sharp rise in the accretion rate onto the AGN.

It is instructive to express the Bondi accretion rate in terms of β . Using equation (5) to determine the electron density, the ratio of the Bondi accretion rate to the ‘‘Eddington’’ accretion rate is

$$\dot{m}_B = \frac{\dot{M}_B}{\dot{M}_{\text{Edd}}} \simeq \frac{\eta \sigma_T c k T_0}{\beta \Lambda(T_0)} \simeq 0.3 \frac{\eta_{-1} T}{\beta \Lambda_{-23}}, \quad (6)$$

where $\Lambda(T_0) = 10^{-23} \Lambda_{-23} \text{ erg cm}^3 \text{ s}^{-1}$, and the ‘‘Eddington’’ accretion rate is defined as usual by

$$\eta \dot{M}_{\text{Edd}} c^2 = L_{\text{Edd}} = \frac{4\pi GM_h m_H c}{\sigma_T}, \quad (7)$$

where L_{Edd} is the Eddington luminosity and $\eta = 0.1\eta_{-1}$ is the radiative efficiency of accretion onto the AGN. The

significant feature to note is that the Bondi accretion rate from the hot gas approaches the Eddington accretion rate as β approaches 1.

3. Outburst Energy

In what follows, it is assumed that, in the absence of feedback from the AGN, the entropy of the gas arriving at the Bondi radius decreases with time due to cooling. However, if the Bondi accretion rate always exceeds the rate at which gas would cool to low temperatures in a simple cooling flow, then Bondi accretion can out-compete cooling and stop the entropy of the gas at the Bondi radius from decreasing. At least for the case of groups and clusters of galaxies, where the old (morphological) estimates of cooling rate greatly exceed the Bondi accretion rate (e.g. Fabian 1994), this cannot occur.

While it is unclear what would bring on an AGN outburst, it seems very likely that it is related to the accretion rate. For example, it has been argued for some time that the radiative efficiency of AGN accretion switches from low to high when the accretion rate exceeds a small fraction of the Eddington accretion rate, \dot{M}_{Edd} (Narayan & Yi 1995; Abramowicz et al. 1995). This may also lead to a sudden increase in the mechanical energy output of the AGN. Alternatively, the accretion rate may need to reach closer to \dot{M}_{Edd} or even exceed it somewhat to cause an outburst. For the purpose of the argument that follows, the only significant issue is that an outburst occurs when the accretion rate reaches some multiple of the Eddington accretion rate that is not a lot more than unity. In that case, we may assume that the gas is approximately hydrostatic at the Bondi radius up to the onset of the outburst.

We can now calculate the mass of gas accreted before the outburst, or, more precisely, the mass of fuel available to power an outburst. The mass accreted in the time interval t_i to t_f is

$$M_a = \int_{t_i}^{t_f} \dot{M}_B dt \simeq \int_{\Sigma_f}^{\Sigma_i} \dot{M}_B t_{\text{cool}} \frac{d\Sigma_0}{\Sigma_0}, \quad (8)$$

where equation (3) has been used to change variable in the integral, and Σ_i and Σ_f are the entropies of the accreting gas at t_i and t_f , respectively. This change of variable involves an approximation, since equation (3) applies to a single fluid element, whereas different fluid elements are continually being accreted. The approximation relies on the gas entering the accretion flow being nearly uniform. In general, it is fairly crude, but we are assisted by two things. First, it is likely that the accreted gas that fuels the outburst comes, initially, from a fairly narrow range of radii (in fractional terms), so that it is likely to be reasonably uniform. Second, the sense of our error is to underestimate dt , hence the total mass accreted. This is because the entropy is a non-decreasing function of the radius in a stably stratified atmosphere and the pressure is a decreasing function of the radius. Both effects mean that cooling is slower at larger radii, so that the decreasing entropy of an outer gas shell lags behind that for an inner one.

Using the Bondi accretion rate (eq. 1) and the cooling time (eq. 4), we find that $\dot{M}_B t_{\text{cool}}$ only depends on the

gas temperature. As argued above, this remains constant until the cooling time is comparable to the sound crossing time at the Bondi radius. Thus the integral gives

$$M_a \simeq \dot{M}_{B,i} t_{\text{cool},i} \ln \frac{\Sigma_i}{\Sigma_f}. \quad (9)$$

While we have only a vague idea of the values to use for Σ_i and Σ_f , the result is quite insensitive to these. We therefore take $M_a = \chi \dot{M}_{B,i} t_{\text{cool},i}$, where the latter two factors can be evaluated at any one time when the cooling time exceeds the sound crossing time at the Bondi radius. Allowing a reasonable range of Σ in the logarithmic factor, and including some correction for the crude approximation involved in the change of variable from t to Σ , reasonable values of χ are of the order of 10.

Using the results from above, we get (again assuming 25 percent helium by mass)

$$M_a \simeq \frac{48\pi\chi(GM_h m_H)^2}{35s_0\Lambda(T_0)} \simeq 2 \times 10^5 \frac{\chi M_9^2}{T^{1/2}\Lambda_{-23}} M_\odot, \quad (10)$$

using the notation from above for the numerical factors. If this mass is accreted onto the black hole and converted to mechanical energy with efficiency η_{mech} , then the energy released is

$$E_a = \eta_{\text{mech}} M_a c^2 \simeq 3.7 \times 10^{58} \frac{\eta_{m,-1} \chi M_9^2}{T^{1/2}\Lambda_{-23}} \text{ erg}, \quad (11)$$

where $\eta_{\text{mech}} = 0.1\eta_{m,-1}$. This is our estimate of the energy available to power an outburst.

4. Application to Hydra A

One of the key assumptions made in the calculation above is that the feedback occurs in outbursts. This is, at least, consistent with the observation that not all cooling flows contain an active central radio source (Burns 1990). If the cooling flows that lack radio sources are in between outbursts, then this also tells us that the evidence of outbursts fades with time. Indeed, the radio lobe cavities, which are the main evidence of mechanical energy input, almost certainly rise buoyantly and disappear, either because the decreasing contrast of the rising cavity makes it difficult to detect, or because the bubbles are non-adiabatic, so that their energy is dissipated and the bubbles collapse. As a result, estimates of outburst energy based on observations of bubbles can only give lower limits to actual outburst energies.

Hydra A is noteworthy for being one of the most powerful Fanaroff-Riley class I radio sources and for having substantial bubbles associated with its radio lobes (McNamara et al. 2000). Using the gas properties from David et al. (2001), the central temperature is $kT \simeq 3$ keV and the central abundance is $Z \simeq 1$, giving the cooling function $\Lambda_{-23} \simeq 1.8$. Sambruna et al. (2000) estimated the mass of the black hole in Hydra A as $M_h \simeq 4 \times 10^9 M_\odot$. Using these numbers in equation (11) gives an outburst energy of $E_a \simeq 2 \times 10^{59} \chi \eta_{m,-1}$ erg.

For the cavity created by the southwest radio lobe in Hydra A, the work required to inflate the cavity is $pV \simeq 2 \times 10^{59}$ erg. This must be added to the thermal energy in the lobe, $pV/(\gamma - 1)$, where γ is the ratio of specific heats for the plasma inside the cavity, to obtain the total

energy required to create the lobe. If the lobe plasma is relativistic, $\gamma = 4/3$ and the energy required to create the lobe is $4pV$. This quantity needs to be doubled again to allow for the northeast cavity, giving a total energy for the bubbles of about 1.6×10^{60} erg. This agrees with the estimate of outburst energy for the model if $\chi\eta_{m,-1} \simeq 8$. Note that, if the expanding cavities drove shocks into the intergalactic medium, then even more energy was required to create them.

Given the uncertainties, these results are broadly consistent with the outburst model described here. Clearly, a lot more data are required to test this model. As discussed above, we should expect to find evidence of a range of outburst energies, extending up to the value given by equation (11). A more detailed model for the evolution of the bubbles is required to determine the distribution of bubble energies we should expect to observe, but we can reasonably expect bubbles to evolve on timescales comparable to their rise times (Churazov et al. 2002). Since these are comparable to the estimated intervals between radio outbursts, a significant fraction of systems are expected to show bubble energies comparable to the outburst energy. Of course, outbursts of significantly greater energy than given by equation (11) could not be accounted for by this model.

The outburst energy in Hydra A is close to the maximum that can be accounted for using equation (11). If the accretion rate remained an order of magnitude or more smaller than the Bondi accretion rate throughout the time between outbursts (Proga & Begelman 2003b), then the AGN could not accrete enough hot gas to power formation of the bubbles in Hydra A. In that case, the AGN would need to be powered chiefly by accretion of cold gas. This result is not sensitive to the model assumptions used here.

5. Conclusions

Heating by AGN feedback may not be the only mechanism that prevents the deposition of cool gas in cooling flows, but it almost certainly plays a significant role. AGN heating may be augmented by other processes, particularly thermal conduction in clusters, but it could be the only heating mechanism required in smaller systems, especially for isolated elliptical galaxies. This is not to dismiss the major gaps in our understanding of the heating process (e.g. Fabian et al. 2001; Brighenti & Mathews 2003).

Because radiative cooling decreases gas entropy, directly increasing the Bondi accretion rate, Bondi accretion of cooling gas onto a central black hole makes a good candidate for part of the AGN feedback process. Here, Bondi accretion is assumed to provide the fuel for AGN outbursts. The Bondi accretion rate climbs close to the Eddington accretion rate as the cooling time at the Bondi radius falls towards the sound crossing time. An outburst can be triggered at about this stage, perhaps when the radiative efficiency of accretion switches from low to high, or later when the luminosity reaches close to the Eddington limit. Accreting gas remains roughly hydrostatic near to the Bondi radius as long as the cooling there is shorter than the sound crossing time. In that case the temperature of gas at the Bondi radius stays close to the virial temperature as the AGN accretes fuel for the outburst. The mass of fuel accreted is then insensitive to the details of when the outburst occurs. This gives an estimate for outburst energy, equation (11), which depends weakly on uncertain details. This outburst energy is determined mostly by the mass of the black hole and the virial temperature of its host galaxy.

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