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Abstract.

Acknowledgments.

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Jet Interactions with the Hot Halos of Clusters and Galaxies

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Abstract. X-ray observations of cavities and shock fronts produced by jets streaming through hot halos have significantly advanced our understanding of the energetics and dynamics of extragalactic radio sources. Radio sources at the centers of clusters have dynamical ages between ten and several hundred million years. They liberate between 10^{58-62} erg per outburst, which is enough energy to regulate cooling of hot halos from galaxies to the richest clusters. Jet power scales approximately with the radio synchrotron luminosity to the one half power. However, the synchrotron efficiency varies widely from nearly unity to one part in 10,000, such that relatively feeble radio source can have quasar-like mechanical power. The synchrotron ages of cluster radio sources are decoupled from their dynamical ages, which tend to be factors of several to orders of magnitude older. Magnetic fields and particles in the lobes tend to be out of equipartition. The lobes may be maintained by heavy particles (e.g., protons), low energy electrons, a hot, diffuse thermal gas, or possibly magnetic (Poynting) stresses. Sensitive X-ray images of shock fronts and cavities can be used to study the dynamics of extragalactic radio sources.

1. X-ray Cavities in Hot Halos

Cavities embedded in hot X-ray halos gauge the energy and power output of recent AGN activity in central galaxies. [1] Cavity systems are found in nearly three dozen clusters (Bîrzan et al. 2004; Dunn & Fabian 2004; Rafferty et al. 2007) and a similar number in giant elliptical galaxies (Nulsen et al. 2006). Like the extragalactic jets that created them, cavities are usually found in pairs. Their surface brightness decrements of several tens of percent are consistent with being nearly devoid of thermal gas at ambient conditions. Most are filled with radio

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[1] See Peterson & Fabian (2006) and McNamara & Nulsen (2007) for recent reviews of this topic, including discussions of theory and simulation which has been omitted from this paper.

emission, and some are connected to the nucleus through synchrotron jets and tunnels in the hot gas (Clarke et al. 2005; Wise et al. 2007, Fig. 3). Many have bright rims composed of cool, dense, gas, ruling-out their association with shock fronts. Most cavities are apparently in pressure balance or are expanding or contracting slowly with respect to their surroundings. In many instances, buoyancy forces are driving them outward. Then their locations with respect to their origin, generally taken to be the nucleus, provide a measure of their dynamical ages, which are generally $\sim 10^7 - 10^8$ yr. Cavity diameters in clusters are typically 20 kpc but can be as large as 200 kpc. In galaxies they are typically a few kpc in diameter. Assuming they form near the nucleus, cavities live long enough to rise beyond their own diameters before breaking apart or fading into the background. Thus cavities must be pressurized and their rims stabilized by motion through the atmosphere (Pizzolato & Soker 2006), plasma viscosity (Reynolds et al. 2005), or magnetic fields draping their surfaces (De Young 2003; Jones & De Young 2005; Lyutikov 2006). In some cases, the cavities appear to be breaking apart where radio plasma is leaking into the ICM (Blanton et al. 2001) or into outer "ghost" cavities (Fabian et al. 2000).

2. Cavity Energetics

X-ray observations provide accurate measurements of the run of gas temperature and density in the halo, and thus its pressure. The projected sizes of cavities and hence their volumes then provide the work, pV, required to inflate the cavity against the surrounding gas pressure (McNamara et al. 2000). Including the energy of the plasma filling them, their total enthalpy can be expressed as $H = \gamma pV/(\gamma - 1)$. The (unknown) ratio of specific heats of the filling plasma, γ, implies a total enthalpy between $2.5pV - 4pV$ per cavity (Churazov et al. 2002). Using the rise time, $t_{\rm rise}$, the average jet power $P_{\rm jet} = H/t_{\rm rise}$ can be found.

Jet power estimated in this manner spans eight orders of magnitude from 10^{38} erg s^{-1} in gE galaxies and up to 10^{46} erg s^{-1} in rich clusters. Typical values in rich clusters are 10^{42} erg s^{-1} to 10^{44} erg s^{-1}, rivaling and sometimes exceeding the total X-ray luminosity of cluster cores. Several clusters and galaxies have weak shock fronts surrounding their radio sources and cavities (Fabian et al. 2003; McNamara et al. 2005; Nulsen et al. 2005; Forman et al. 2005), two of which are shown in Fig. 3. Mildly transonic Mach numbers $\sim 1.2 - 1.6$ are found in clusters, while stronger shocks are found in lower mass giant elliptical systems (Kraft et al. 2003). The outburst energy estimated independently from shocks lies reassuringly within small multiples of the cavity power. Thus, jet power estimated by cavity dynamics provides a reliable lower limit to the total mechanical energy dissipated by radio jets.

3. Feedback in Galaxies & Clusters

Cavity systems are found preferentially in galaxies and clusters whose hot halos have cooling times $\leq 5 \times 10^8$ yr (Dunn & Fabian 2006). In such systems gas is expected to cool at rates of ≤ 1 M$_\odot$ yr^{-1} in gEs and $100 - 1000$ M$_\odot$ yr^{-1} in clusters. However, high- and moderate-resolution X-ray spectroscopy made with the Chandra and XMM-Newton X-ray observatories failed to detect the characteristic emission below 1 keV from gas cooling at these rates (Peterson & Fabian 2006). This implies that gas is either cooling non-radiatively into an unseen form, or the gas is maintained at high temperatures by a powerful and persistent energy source. The former idea has been essentially ruled out by sensitive searches for such a repository carried out during the past three decades. However, several viable energy sources have been explored, including thermal conduction from the hot outer halos, AGN, mergers, cosmic rays, and other mechanisms. All of these mechanisms may be operating in one system or another to a greater or lesser degree. But AGN feedback appears to be operational and energetically important in most halos where heating is required to offset cooling.

There are several lines of supporting evidence. First, the apparent ubiquity of supermassive black holes (SMBH) in the nuclei of bulges (Magorrian et al. 1998) and the high efficiency with which SMBHs convert gravitational binding energy into mechanical energy and heat make them an ideal and nearly universal source of energy in hot halos.

Second, nearly 70% of cooling flow clusters with high cooling rates have active cavity systems and or radio sources indicating they are "on" much of the time (Dunn & Fabian 2006). Roughly 20% of gEs harbor detectable cavity systems (Nulsen et al. 2006). AGN liberate on average the right amount of energy to balance radiative losses over many orders of magnitude of power in isolated gE galaxies to the richest clusters. Roughly half of cluster cavity systems are underpowered and those preferentially experience star formation at rates of several to several tens of solar masses per year (Rafferty et al. 2006, 2007). In contrast, all of the gE cavity systems are overpowered relative to their cooling luminosities and should be able to quench star formation at late time, as is observed. A picture of this feedback sequence adapted from the heating and cooling diagrams of Bîrzan et al. (2004), Dunn & Fabian (2006), and Nulsen et al. (2006) but painted with a broad brush is given in Fig. 1. There are individual exceptions to the partitioning in this diagram, but it provides a reasonably good characterization.

Third, feedback from a central source appears necessary to maintain the high gas densities and short central cooling times (Voigt & Fabian 2004) without allowing catastrophic cooling. Finally, cluster halos show entropy cores indicating a history of central energy injection that is consistent with the current rate of cavity injection (Voit & Donahue 2005). We still do not understand how AGN heat the gas, although there are many ideas (see McNamara & Nulsen 2007, for further discussion). This problem will hopefully sort itself out over the next several years.

4. General Consequences of Feedback in Clusters

AGN feedback lies at the heart of several problems in galaxy formation, including the exponential decline rather than the expected power law behavior of the bright end of the galaxy luminosity function (Benson et al. 2003), the existence of the Magorrian (1998) relation (the correlation between SMBH mass and bulge mass), and "cosmic downsizing," the anti-hierarchical tendency for the most massivive galaxies to lie dormant while low mass systems burgeon with star formation at late time (Juneau et al. 2005). Each may be a consequence of feedback of one

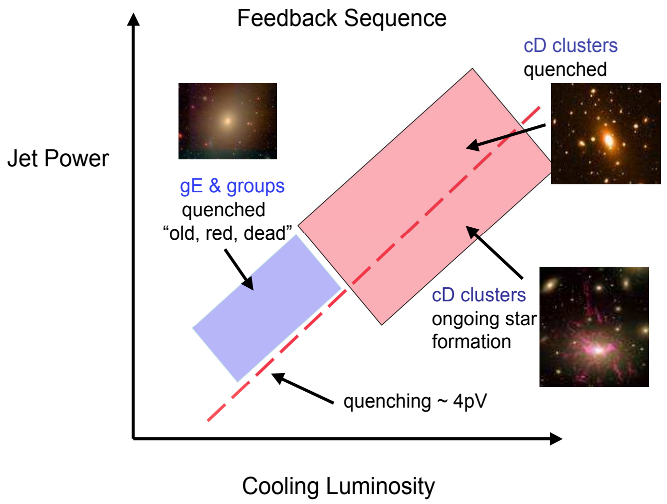

Figure 1. Depiction of conjectured AGN feedback sequence that runs from giant elliptical halos (lower left) to rich clusters (upper right). Objects lying above the “quenching” line are energetically able to maintain their halos at X-ray temperatures at the present time.

form or another, although AGN surely dominate in massive systems. Cooling flows are interesting and particulary important in this respect. They are among the few if only systems where cooling, star formation, and feedback in large halos are clearly manifest such that the theory of feedback and jet interaction can be tested in detail. The spate of discoveries of cavities and shock fronts in hot halos over the past eight years has provided much of the impetus for new, feedback-based models of galaxy formation and evolution. Finally, cluster-scale outbursts like those in Fig. 3 may contribute significantly to the excess entropy (“preheating”) in groups and clusters (Voit & Donahue 2005).

5. Using Cavities to Gauge AGN Mechanical Power

5.1. Synchrotron Radiation Efficiencies of Radio Sources

Cavity systems and their associated shock fronts provide a reliable probe of the energetics and dynamics of radio outbursts. It is commonly held that the energy in a radio source is partitioned between particles and magnetic fields, $E_{\rm tot} = E_{\rm B} + E_{\rm p}$. Radio observations of jets and lobes measure their synchrotron radiation, revealing the existence of relativistic electrons and magnetic fields, but not their total power. It has long been thought that the total power is dominated by the mechanical work driving their expansion (Scheuer 1974). However, prior to Chandra, the total energy had to be inferred indirectly (e.g., Willott et al. (1999). A measure of the ratio of total jet power to synchrotron power is given by the radiative inefficiency ratio $\epsilon = P_{\rm jet}/L_{\rm syn}$. The magnitude of this ratio is

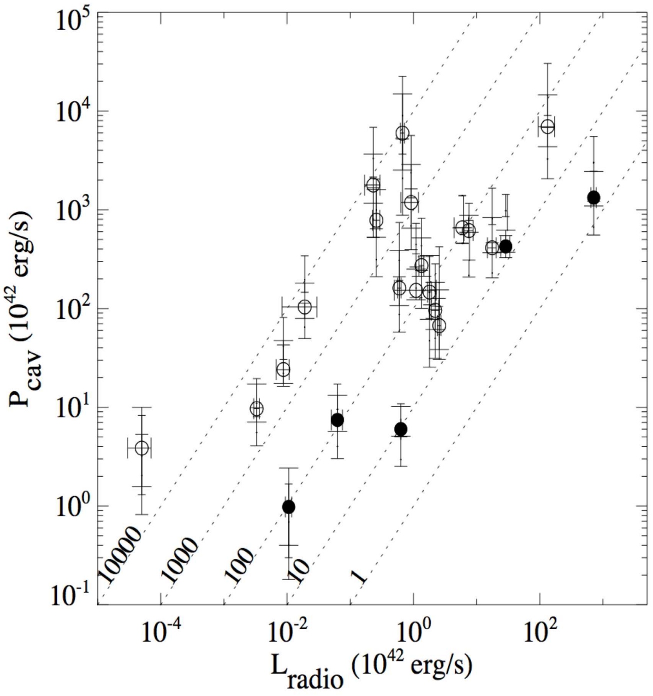

Figure 2. Cavity power versus bolometric synnchrotron power in the cavities alone from Bîrzan et al. (2007). Diagonal lines represent constant values of ϵ. Solid points are cavity systems that have significant 8 GHz emission.

often assumed to lie between a few and 100, with $\epsilon = 10$ taken as a reasonable estimate for many sources.

An early systematic cavity study by Bîrzan et al. (2004) based on radio data taken from the literature found that jet (cavity) power scales with radio synchroton luminosity to the one half power, but with a very large scatter in ϵ. Bîrzan and colleagues have recently updated this work with new VLA observations of 23 cavity systems at three or more frequencies, shown in Fig. 2. Her work has confirmed the reality of the trend and the large variations in ϵ. The median $\epsilon_{\rm med} \simeq 120$ for the lobes alone, but the average $\epsilon_{\rm av} \simeq 4700$ is dramatically larger. The range includes values of approximately unity for the youngest sources and more than 10,000 in the case of the cavity system in the HCG 62 group. Note that these figures are underestimates as they do not include the energy released by shocks, which can be factors of several larger. ϵ is almost surely not constant in time, and is expected to increase due to adiabatic expansion and synchrotron aging. But these factors may not account for such large variations, and there may be substantial intrinsic variations in ϵ.

This result is consequential in several respects. It shows quantitatively that FR I-type AGN are on average strongly dominated by mechanical energy. In some cases, feeble FR-I sources with dynamical ages of a few tens of Myr are as mechanically powerful as luminous quasars. Thus, feedback from modest radio sources can have a dramatic effect on their environment by driving outflows, stifling star formation, and quenching cooling flows. The unexpectedly large variation in ϵ is one of the principal reasons that AGN have only recently become widely recognized as a viable quenching mechanism for cooling flows. Finally, it is unfortunate news for galaxy formation modelers and observers seeking a simple prescription for feedback based on radio surveys of galaxies. There is no simple conversion between jet power and synchrotron luminosity. The situation is more complex than we might have hoped.

5.2. Jet & Lobe Contents

The dependencies in the energy equation can be expressed as:

$$E_{\rm tot} = E_{\rm B} + E_{\rm p} \propto \frac{B^2}{8\pi}\Phi V + A(1+k)L_{\rm syn}B^{-3/2},$$

where B is the magnetic field strength in the lobes, V is the lobe volume, $L_{\rm syn}$ is the bolometric synchrotron luminosity, Φ is the field filling factor, and k is the ratio of energy in particles to that in electrons. Additional terms may be required to account for additional sources of pressure. A hot, diffuse thermal plasma is an obvious example.

X-ray observations provide several constraints. $E_{\rm tot} \sim pV$. Φ is inferred to be close to unity or cavities, which are difficult to detect under ideal circumstances, would be invisible were they not nearly swept of ambient gas. Cavity volumes are estimated from their projected sizes. Only $L_{\rm syn}$ is measured with radio observations at several frequencies using instruments such as the Very Large Array. This leaves k and B as free parameters that can be inferred statistically from large samples of cavities under the (reasonable) assumption of pressure balance with their surroundings.

Analyses along these lines were presented by Dunn & Fabian (2004) and Dunn et al. (2005). Using radio data taken from the literature, they found a large variation in k such that $1 \leq k \leq 1000$. In most systems $k > 1$ indicating that the energy is dominated by heavy particles. De Young (2003) reached a similar conclusion by treating observed jets as pipe-like conduits through which all of the energy in cavities must pass in a timescale comparable to the synchrotron and dynamical ages. He found the required energy desities within the jets must be so much larger than the surrounding gas pressures that jets would quickly decollimate unless the jet fluid is composed of heavy particles (eg., protons) with an anisotropic pressure field. Otherwise, the jets must be actively collimated by magnetic fields, for example, which has its own complications, or perhaps they are dominated by electromagnetic flux (e.g., Blandford 1976; Nakamura et al. 2007, this conference).

Using the new VLA sample, Bîrzan et al. (2007) found a similarly large variation in k, but in general $k >> 1$ and $B \leq 50\mu$G inside the lobes. B and k vary widely from system to system. How much of this is intrinsic or is a consquence of degeneracy between B and k and other assumptions is less clear. There are indications that k may be somewhat time dependent due to synchrotron aging and adiabatic expansion. But the findings of large k appear to be robust. It may be difficult to get around the conclusion that that FR I radio sources in clusters are heavy. It is less clear that they are born that way or become heavy by entraining ambient material as they advance.

Other possibilities include a dominant population of mildy relativistic, low energy electrons (Willott et al. 1999). The large ks may be a consequence of a missing third term accounting for additional pressure support by a hot thermal plasma. Limits on such a plasma indicate gas temperatures $T \geq 15 - 20$ keV (see McNamara & Nulsen 2007, for references and a discussion). Finally, it was pointed out in this conference by Hui Li and his collaborators that their models of current-carying Poynting jets moving in pressure balance with the surrounding gas are able to reproduce the distribution of cavity sizes with nuclear distance found by Rafferty et al. (2006) and Wise et al. (2007).

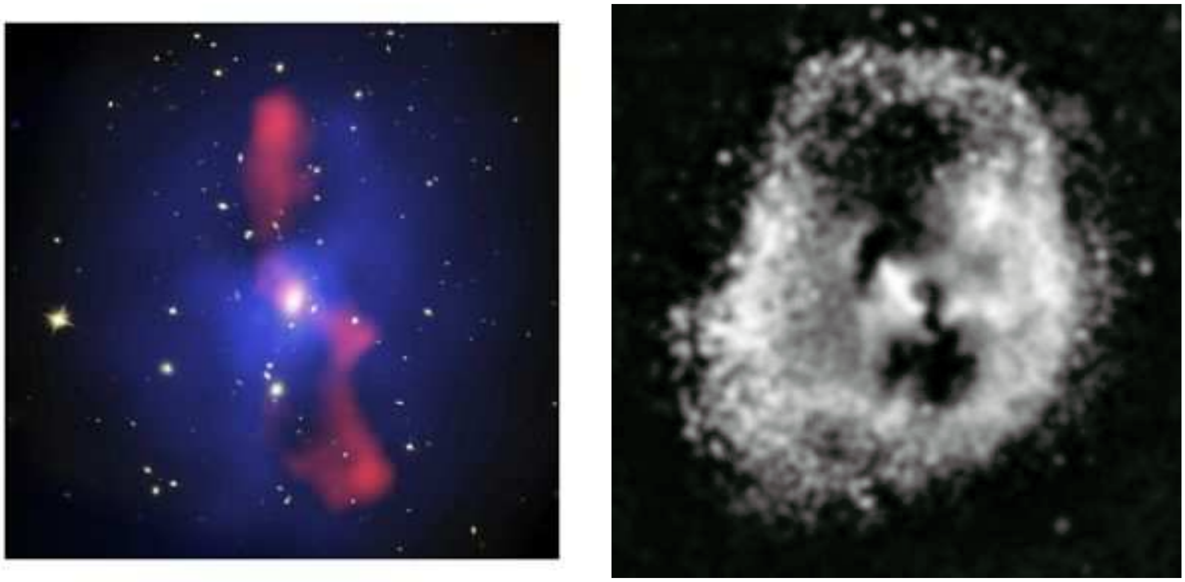

Figure 3. Two cluster-scale AGN outbursts with powers exceeding 10^{61} erg. MS0735.6+7421 is shown at left (McNamara et al. 2005) and Hydra A (Wise et al. 2007) is shown at right. In MS0735, X-rays are in grey, 327 MHz emission (Bîrzan et al. 2007) is in white as are the galaxies. The twin cavities are each roughly 200 kpc (one arcminute) across. This figure is available in color at the public websites of the Chandra X-ray and Hubble Space Telescope Observatories. The central $\simeq 12$ arcmmin (750 kpc) of Hydra A (right) in X-rays is filled with a complex system of cavities. The central cavities of McNamara et al. (2000) each roughly 20 kpc in diameter are dwarfed by the outer cavities. The largest cavity to the north (cavity E of Wise et al. 2007) lies 226 kpc from the nucleus and has a diameter of roughly 200 kpc. The entire cavity system is filled with 327 MHz radio emission (Lane et al. 2004). The cavity systems in both clusters are enveloped by weak shock fronts.

5.3. Equipartition

Adopting the well justified assumption that cavities are in pressure balance with their surroundings, one can evaluate whether the pressure support can be supplied by a plasma in equipartition between electrons and magnetic field. Results for individual objects, such as Abell 2052 (Blanton et al. 2001), have shown that the internal lobe pressures must exceed the equipartition values in order to maintain pressure balance with the ambient gas. Dunn's (2005) analysis and Bîrzan's new analysis of 19 systems (for $k < 100$) both find this to be true in general. Equipartition pressures lie a factor of 10 or more below the values required to maintain pressure balance, apart from a few systems, such as Cygnus A and the inner cavities of Hydra A.

6. Jet and Lobe Dynamics

Bîrzan's radio analysis permits a comparison of the cavity buoyancy (dynamical) ages to their synchrotron ages, providing an independent check on both quantities. The ages agree in several instances. However, by and large the cavity ages exceed the synchrotron ages by factors of several to several tens. These differences probably reflect to some degree weaknesses in the foundations of both age estimates. A strong constraint can be placed on the relative ages by the presence or absence of strong shocks in the hot halos. In order to bring the dynamical ages into agreement with the synchrotron ages outward velocities that are factors of several to several tens larger than their buoyancy speeds are implied. These speeds are highly supersonic. Such fast moving cavities would create strong shocks with Mach numbers much higher than those observed. Overall, the data suggest that the radiation ages and the dynamical ages of these systems are decoupled.

Another check on the buoyancy ages can be made by comparing them to the entirely independent ages of the shock fronts that sometimes accompany them. This check has been performed in MS0735 and Hydra A, and in both cases the ages agree to within a factor of two. Hydra A is interesting in that the buoyancy age of the large outer cavity to the north shown in Fig. 3 (cavity E of Wise et al. 2007) is 220 Myr compared to the shock age of 140 Myr. Although they are in formal agreement, taken at face value these ages are inconsistent with each other if the cavities are currently driving the shock. The implications are that either the cavities are still being driven by the jets and thus the buoyancy age overestimates the true age, or the cavities form far from the nucleus. It is possible, though less likely, that the shock formed later and has just overrun the outer cavities.

The ratio of energy in the cavities to that in the shock fronts can in principle indicate whether the AGN is ramping up or down. Both in Hydra A and MS0735 this ratio is only modestly less than unity, indicating that the jets are still powering the cavities. The situation in Hydra A is complex (see Fig. 3), and thus a clear picture has yet to emerge. The point here is that deep Chandra observations combined with multiple frequency radio observations of cavity and shock systems have the potential to provide a detailed view of the dynamics of extragalactic radio sources.

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