Proceedings of *The Riddle of Cooling Flows in Galaxies and Clusters of Galaxies*: E19
May 31 – June 4, 2003, Charlottesville, Virginia, USA
Ed. T. H. Reiprich, J. C. Kempner, & N. Soker

The interaction of jets with the intracluster medium

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The interaction of relativistic AGN jets with their surroundings produces a number of features observable in the X-ray band, such as shocks, sonic boom compressions, and X-ray cavities. Based on simple analytic arguments, one can show that strong shocks play only a minor role in heating the cluster gas in cooling flows and that there is strong observational bias against detecting such strong shocks (thus implying that the absence of observational evidence for strong shocks around X-ray cavities does not imply that they do not occur during the appropriate phase of radio galaxy evolution). Furthermore, analytic estimates show that X-ray cavities are more easily detected in systems where the jet is oriented perpendicular to the line of sight, i.e., in systems with double sided jets.

1. **Introduction**

Relativistic jets in active galactic nuclei (AGNs) carry enormous amounts of energy, which they ultimately deposit into their environment. Because this energy can, at least in principle, be transferred to the interstellar and intracluster medium (ICM), AGN jets have received heightened attention as a possible mechanism for heating the X-ray gas in clusters of galaxies, especially in cooling flow clusters. Thus, particular emphasis was placed at this conference on the possible role radio galaxies (i.e., AGNs with powerful jets) play in the puzzle posed by the missing cool gas in cooling flow clusters.

The energy delivered by the AGN jet is primarily in the form of kinetic energy of the jet plasma. The total amount of energy released by a powerful jets at the transition from FR I to an FR II (Fanaroff & Riley 1974) radio galaxies (where most of the total power by radio galaxies is delivered into the universe) is of order $L_{\rm kin} \gtrsim 10^{44}\,s^{-1}$, which is sufficient to provide the energy to heat the interior of a cooling flow cluster.

As argued by Churazov and Nulsen in these proceedings, the feeding mechanism of AGNs by accretion of gas within their Bondi radius is well suited for the type of feedback needed for heating cooling flow clusters — whenever cooling in the center increases, the accretion rate of the AGN increases, thus increasing the heating rate, counteracting the gas cooling.

The main question about jet heating of cooling flows is therefore not so much whether they can provide sufficient energy in principle, or whether they can provide it at the right time (though the details of the thermostat nature of AGN fueling are still to be worked out, since Bondi accretion is almost certainly not the mechanism by which material is funneled to the inner regions of the disk), but rather, how the energy is transferred to the environment.

We can learn how this transfer takes place by studying the interaction of radio plasma (traveling down the jets) with the ICM by a combination of theoretical modeling with X-ray and radio observations. Such studies are worthwhile for other reasons as well: The dynamical behavior of radio lobes (the plasma depositories for spent jet fuel, in the following used synonymously with the expression “bubble”) can be used to infer such important quantities as the jet power and the jet intermittence timescale. The study of jets on the largest scales can therefore yield important information about the nature of jets right down to the horizon scale of the central black hole.

The following sections present some thoughts on how the interaction of AGN jets with the ICM takes place and how it will be best observable.

2. **Lobe Evolution**

The general picture of the evolution of radio jets and lobes launched from a black hole at the center of the galaxy cluster is as follows: The interaction between the jet and the environment typically occurs in a shock (called the working surface), which slows the jet material down to sub-relativistic speeds and releases relativistic plasma into the environment. This plasma inflates the radio lobes. Initially, these radio lobes are strongly overpressured with respect to the environment, thus expanding supersonically, driving a strong shock into the ICM. This phase has been modeled successfully both analytically (Kaiser & Alexander 1997; Heinz et al. 1998) and numerically (e.g., Reynolds et al. 2001; Scheck et al. 2002).

One of the early ideas of radio galaxy feedback in the ICM was that it is this strong shock that heats the ICM, because shocks are very efficient dissipators. However, as will be argued below, this is not the case, and other forms of heat input should be more prominent. Nevertheless, **every** radio lobe **must** initially be strongly overpressured and supersonic, thus driving a strong shock into the ICM. This phase is not optional, and the absence of strong shocks in observations of X-ray cavities by the *Chandra* X-ray observatory does **not** imply that they do not occur — the absence of evidence is not the evidence of absence.

As the lobe grows, the expansion slows down, passing through a trans-sonic phase, where the strong external shock turns into a mild shock or expansion wave (Reynolds et al. 2001). Eventually the expansion becomes subsonic. At this point, the radio lobes - essentially large plasma bubbles, start feeling the buoyancy induced by the gravitational potential of the host cluster. They detach in about a lobe sound crossing time and float up the gravitation potential well. Because the radio plasma displaces the X-ray emitting cluster atmosphere, the radio lobes are visible as depressions in the X-ray surface brightness, i.e., as X-ray cavities.

Depending on the duty cycle of the jet itself, the subsonic lobes might still be actively fed with energy by the jet, however, they will detach roughly at this point, and the following discussion still applies. If the jet turns off significantly before detachment, the discussion below will be somewhat modified. It is also possible that the jet will itself become subsonic before the bubbles detach, for example due to mass loading by entrainment (Bicknell 1995), which is believed might be occurring in FR I type jets. Again, this should not change the dynamical picture significantly, as long as the plasma released by the jet is still relativistic, and the expansion is governed by the rate of energy injection.

It was argued in the literature (Reynolds & Begelman 1997; Kaiser & Alexander 1997; Heinz et al. 1998) that the evolution of the radio lobes can be modeled rather successfully by making a self-similar ansatz. In the simplest version, this model employs spherical symmetry and assumes that the environment is described by an isothermal power-law atmosphere in density,

$$\rho_{\rm ICM} \propto r^{-\zeta}\,. \tag{1}$$

This basic model is sufficient to arrive at some simple, yet general statements about the evolution of radio lobes.

In this picture, the radio plasma is described as a hot medium with uniform pressure, which is strongly overpressured with respect to the environment. Thus, its internal pressure is governed by the ram pressure of the swept up external medium. Energy and momentum conservation and an adiabatic equation of state can then be combined to provide the evolution equation for the radius $R_{\rm lobe}$ of the expanding bubble (Heinz et al. 1998):

$$R_{\rm lobe} \propto \left(L_{\rm jet} t^3/\rho_{\rm ICM}\right)^{1/(5-\zeta)}\,, \tag{2}$$

with a constant of proportionality weakly dependent on ζ. Here $L_{\rm jet}$ is the mean kinetic luminosity of the jet and $\rho_{\rm ICM}$ is the external density at some reference point (typically the core radius $R_{\rm c}$).

Because eq. (2) is only valid in the regime where the lobe is strongly overpressured (thus enabling us to neglect the gas pressure of the environment compared to the ram pressure it exerts), this description breaks down once the lobe becomes subsonic (see next section). However, since buoyancy will detach the bubble shortly thereafter (within a few sound crossing times, i.e., a few times the dynamical age of the bubble at that point), it is convenient to divide the evolution into the supersonic and the subsonic stage. The remainder of this section will concentrate on the supersonic phase, while the next section focuses on the buoyant part.

Equation (2) describes the evolution of the radio lobe with time, and its time derivative directly provides the expansion speed of the radio lobe. Given the sound speed of the external medium $c_{\rm ICM}$, we know the Mach number as a function of time. We can then invert this relation and find the fraction $P(>M)$ of time during which a radio lobe expands faster than a given Mach number M, over the total time during which lobe expansion is supersonic:

$$P(>M) = M^{-(5-\zeta)/(2-\zeta)}\,. \tag{3}$$

Typically $0 < \zeta < 1.5$, and so typically $P(>M)$ lies somewhere between $P(>M) = M^{-2.5}$ and $P(>M) = M^{-7}$, which implies strong dependence on M. E.g., in the most optimistic case of a constant density atmosphere ($\zeta = 0$), a radio galaxy spends less than 18% of its supersonic life at Mach numbers larger than 2 and less than 3% of its life at Mach numbers larger than 4. For more realistic values of $\zeta > 0$, these fractions become much smaller.

Thus, most of the expansion of the lobe is only mildly supersonic, even if we neglect the subsonic evolution that follows. As a consequence, it is statistically very unlikely to catch a radio lobe and the associated X-ray cavity in the strongly supersonic phase. Since the supersonic expansion occurs during the early stages when the bubble is still very small, it will be very difficult to detect the associated X-ray cavity due to its small angular scale. Finally, since the associated shock temperatures are high, it will be difficult to detect the associated shell with current instruments, since its emission will be shifted out of their band pass. It is therefore not too surprising that the cavities found by the *Chandra* X-ray observatory are all in the mildly supersonic or subsonic regime (e.g., Fabian et al. 2000; McNamara et al. 2000; Blanton et al. 2001).

It is worth noting that this relation is independent of jet power and of the external density and sound speed. It should therefore be rather generally applicable.

The fact that the lifetime of strong shocks is short suggests that their impact on the ICM is also limited. Since we know the size $R_{\rm lobe}$ of the lobe at any given time and thus at any given Mach number, we can integrate eq. (2) to obtain the mass within a given radius R. As the bubble expands, it sweeps up mass and processes it through a shock of Mach number $M(R)$. We can thus calculate ratio $\xi(>M)$ of the mass $m(>M)$ that passed through a shock with Mach number larger than M, relative to the total mass $m(M>1)$ that was swept up in the supersonic phase, i.e., $\xi(>M) = m(>M)/m(M>1)$:

$$\xi(>M) = M^{-3(3-\zeta)/(2-\zeta)}\,. \tag{4}$$

Again, $\xi(>M)$ will fall into the range of $\xi(>M) = M^{-4.5}$ and $\xi(>M) = M^{-9}$ for $0 < \zeta < 1.5$. Thus, even for $\zeta = 0$, only 5% of the total shocked ICM mass go through a shock stronger than M=2, and only 0.2% go through a shock stronger than M=4, with even smaller fractions for larger values of ζ.

This shows that only a small fraction of the mass is processed in a strong shock, and most of the mass goes through only mildly supersonic shocks, even if we neglect the subsonic evolution. This completes the argument why strong shocks play only a minor role in heating the ICM.

3. **Buoyant Bubbles**

During the subsonic phase, the external gas pressure becomes dominant, and thus effects linked to the stratification of the external atmosphere govern the evolution of the bubble. Because the light relativistic gas inside the bubble is Rayleigh-Taylor unstable under the heavier ICM, the two lobes of the radio galaxy will separate from the center and float upward the gravitational well.

The bubble will separate once the expansion speed of the bubble becomes smaller than the buoyant rise velocity. In the limit of small bubbles, this buoyant rise velocity can be estimated by balancing the buoyancy force felt by the bubble with the ram pressure of the cluster gas (multiplied by the hydrodynamic drag factor $c_{\rm W}$), while for large bubbles it is about half the sound velocity. As the bubble rises, it performs $p - dV$ work on its environment, some of which might be converted to heat through turbulence (Ruszkowski & Begelman 2002; Brüggen & Kaiser 2002), or viscosity (Fabian et al. 2003,also: these proceedings). This article will not comment on the aspect of subsonic, buoyant cluster heating beyond stating that it is probably more important than supersonic heating.

While the detailed dynamics of such buoyant bubbles can be rather complicated (depending on things like vorticity carried within the bubbles, the onset of Kelvin-Helmholtz instabilities, and entrainment of cold ICM into the hot bubble gas), we can once again gather some interesting insight into the process by considering a simple analytic model. Enßlin & Heinz (2002) discussed the dynamics of light (i.e., the inertia of the bubble material is negligible) spherical bubbles in isothermal beta-model atmospheres, where the ICM density follows $\rho_{\rm ICM} \propto [1 + (r/r_{\rm c})^2]^{-3\beta/2}$ with some core radius $r_{\rm c}$.

In this case, the position and size of the bubble are related to the rise time through incomplete Beta functions, and it is straight forward to cast the depression of the X-ray surface brightness and of the total X-ray flux due to the presence of the bubble into analytic form (Enßlin & Heinz 2002).

These expressions provide useful estimates for observability constraints of X-ray cavities. In particular, it is useful to consider the contrast in surface brightness between a line of sight through the center of the bubble and a line of sight through undisturbed gas at the same projected distance to the cluster center. Rather than rewriting the mathematical expressions from Enßlin & Heinz (2002), it is sufficient for the purpose of this argument to show a plot of the X-ray contrast as a function of the position r of the bubble in the cluster in Fig. 1 (for typical cluster parameters), adapted from Enßlin & Heinz (2002), which the interested reader is encouraged to consult for details.

As the bubble rises, the X-ray contrast between cavity and undisturbed ICM decreases, as expected. More strikingly, however, the viewing angle relative to the bubble trajectory has a strong effect on the observability of the bubble: Bubbles traveling perpendicular to the line of sight (i.e., in the plane of the sky, indicated by the 0° line in Fig. 1) can have several orders of magnitude larger X-ray contrast than bubbles traveling along the line of sight (indicated by the 90° line in Fig. 1). In other words, it will be much easier to detect a bubble that is traveling perpendicular to the line of sight.

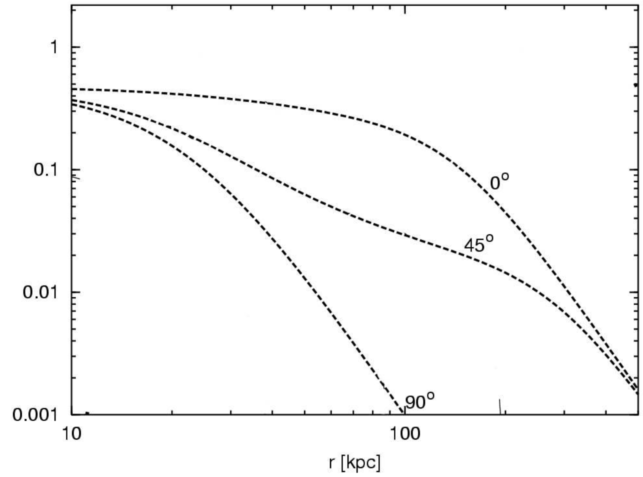

FIG. 1.— Cavity X-ray contrast: Ratio δ of the difference $\Delta\Sigma$ between the X-ray surface brightness $\Sigma_{\rm cavity}$ of a line of sight through the center of the cavity and the surface brightness $\Sigma_{\rm ICM}$ of a line of sight through unperturbed cluster gas at the distance to the center over the surface brightness $\Sigma_{\rm ICM}$ of the unperturbed gas, i.e., $\delta = (\Sigma_{\rm ICM} - \Sigma_{\rm cavity})/\Sigma_{\rm ICM}$; adapted from Ensslin & Heinz 2002 with typical cluster and bubble parameters (core radius $r_{\rm c} = 20\,{\rm kpc}$, initial bubble size 10 kpc, external sound speed of $c_{\rm s} = 1400\,{\rm km/s}$, $\beta = 3/4$).

Since the bubble trajectory is dictated by the elongation of the initial radio lobe, and since this elongation is set by the orientation of the jet, this selection bias translates into a bias that strongly favors the detection of X-ray cavities from jets oriented perpendicular rather than parallel to the line of sight. Such jets are **not** relativistically boosted towards us and should therefore typically be double sided. Large scale motions and non-sphericity in the ICM will complicate this argument. Nonetheless, it would be very interesting to compare this prediction with the statistics of observed cavities and their associated jets. Measurements of bubble sizes and positions also allow us to put constraints on the jet power and life time (e.g. Blanton et al. 2001; Churazov et al. 2000; Heinz et al. 1998, 2002). It would therefore be extremely helpful to compile a flux limited sample of X-ray cavities in galaxy clusters.

4. **Conclusion**

Based on simple, yet generic analytic estimates, it was argued that strongly supersonic expansion is relevant only to the early phase of radio galaxy evolution. This implies that there is a strong selection bias against detecting strong shocks surrounding X-ray cavities, and that strong shocks play only a minor role in heating the ICM. Based on similarly simple analytic estimates (Enßlin & Heinz 2002), it was argued that the strong dependence of the X-ray surface brightness contrast between X-ray cavities associated with radio lobes and the undisturbed cluster gas produces a selection effect favoring detection of bubbles traveling in the plane of the sky, while disfavoring bubbles along the line of sight. This implies that it should be much easier to detect bubbles from double sided jets than from one-sided, beamed jets.

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