Proceedings of *The Riddle of Cooling Flows in Galaxies and Clusters of Galaxies*: E10
May 31 – June 4, 2003, Charlottesville, Virginia, USA
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Intracluster Magnetic Fields and the Reheating of Cooling Flows

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The total energies present in extended radio sources could, in principle, play a significant role in the overall energy balance of the intracluster medium. The presence of magnetic fields in the intracluster medium is well established, and the role of ICM magnetic fields in influencing the evolution of cluster radio sources and the deposition of radio source energy into the ICM is examined. The use of analytical and non-linear numerical MHD calculations shows that intracluster fields can delay the onset of instabilities that mix radio source material with the ICM for times up to $\sim 10^8$ yr, and the turbulent cascade that occurs when mixing finally does take place can be delayed for as long as $\sim 10^9$ yr after the birth of the radio source. These processes are directly related to possible reheating mechanisms being suggested for the ICM.

1. **Introduction**

The interaction of extended radio sources in clusters of galaxies with the intracluster medium (ICM) has been inferred since the first observations of "head-tail" radio sources over two decades ago. However, direct observation of this interaction required imaging of the ICM itself, and the first hints of this came from Einstein observations of Cygnus A (Harris et al. 1994). More recent high resolution X-ray observations with the Chandra Observatory have provided clear and dramatic evidence for the interaction of radio sources with the hot intracluster medium (e.g., Fabian et al. 2000). These images, when coupled with high resolution radio observations, clearly show the extended radio source lobes displacing the X-ray emitting gas and forming a cavity in the ICM. In general these cavities show a rather regular morphology, suggesting the presence of a "relaxed" structure that is in approximate equilibrium with its surroundings. There is no evidence for a high temperature layer surrounding the cavities that would be produced by a shock front; in some cases the region of bright X-ray emission surrounding cavity has a lower temperature than the ambient ICM (Nulsen et al. 2002). All of this is suggestive of slow, subsonic inflation rates for the cavities, and if they are in pressure equilibrium with the ambient ICM, then their internal energy densities exceed the minimum equipartition energy densities by roughly an order of magnitude (McNamara et al. 2001).

1.1. *The Influence Upon Cooling Flows*

The geometries and energy densities of the radio cavities naturally suggest the occurrence of buoyant motion through the hot ICM in the presence of the gravitational potential of the central galaxy and cluster core. The evolution of such buoyant cavities has been suggested to be an important factor in the evolution of cluster cooling flows. It has been known for many years that the total energies present in extended radio sources in clusters (10^{57}–10^{59} erg) are enough to significantly influence the overall energy budget of the ICM. The problem has been, and may still be, in finding an effective mechanism for mixing this energy uniformly throughout the inner regions of the ICM. Several authors have recently suggested that buoyant radio cavities can accomplish this, either through advective mixing of differing regions of the ICM at different temperatures or through the dissolution of the radio cavities and the dispersal of their energetic and hot radio plasma into the ICM. The two-dimensional axisymmetric hydrodynamic calculations of Reynolds et al. (2002) show some advection of cooler intracluster material into hotter regions of the ICM, though it is less clear that a truly buoyant cavity is seen in these simulations. The three-dimensional hydrodynamic calculations of Brüggen et al. (2002) show more clearly the development of a buoyant cavity, and these simulations also show the development of Rayleigh-Taylor instabilities that lead to mixing with the ICM and eventual destruction of the cavity as a separate entity. This process could in principle inject a significant amount of energy into the ICM and can be more effective for reheating than the mixing of different regions of the ICM via advection, though this is also seen in the simulation of Brüggen et al. (2002). The two-dimensional very high resolution hydrodynamic simulations of Brüggen & Kaiser (2002) show very clearly the onset and non-linear development of surface instabilities in the rising cavity, and these calculations show that the cavity is destroyed and mixing well underway after the cavity has risen only a few of its own diameters. Presumably in three dimensions this process would be even more effective due to the larger number of modes available for the development of the instability. Thus hydrodynamic consideration of buoyant cavities in the ICM show that very significant mixing of the cavity material with the ambient ICM can occur on short timescales, of order 10^7 years, and this can transfer a significant amount of the energy from the radio source plasma to the intracluster medium. The final mixing of this material throughout the ICM has yet to be calculated; Brüggen & Kaiser (2002) provide an estimate of what might be the final state of the ICM after such mixing by averaging the energy input from the buoyant plumes over azimuth. This estimate shows that, if complete mixing can occur on a time short compared with inflow times, the injection of energy from radio sources can be a significant factor in reheating cooling flows and hence may be one solution to the long standing cooling flow problem.

2. The Evolution of Relic Radio Bubbles

Recently new radio and X-ray observations have revealed an additional feature in the intracluster medium of some rich clusters, and this is the presence of pairs of what appear to be relic radio "bubbles" that lie well outside the more luminous radio cavities in the inner core of the ICM. Spectacular examples of this phenomenon are found in the Perseus (A426) and A2597 clusters, though other examples have also been found (McNamara 2002). These relic bubbles are coherent objects that are nearly spherical in appearance and have radio emission at low frequencies but are not easily seen at high frequencies (Fabian et al. 2002). They also appear to be in equipartition with the ambient ICM at pressures of 1–4 $\times 10^{-10}$ dyne cm^{-2}, and if so then they have internal energy densities that are again in excess of the equipartition values by factors of ten. The buoyant rise times to their current positions from the central galaxy are of order 10^8 years, which exceeds the radiative lifetimes of the electrons in the inner lobes by factors of ten (McNamara et al. 2001; Churazov et al. 2001). This implies the need for electron reacceleration (see also Brüggen et al. 2002).

2.1. *The Role of Intracluster Magnetic Fields*

In light of the results from the numerical simulations, one of the most surprising aspects of the relic radio bubbles is that they are intact. If such objects were to follow the evolutionary path described by hydrodynamic simulations, one would expect that at distances $\sim$ 30 kpc from the cluster center and at times $\sim 10^8$ years the radio remnants would have become fragmented and assimilated into the ambient intracluster medium. The fact that they have not done so may have important implications for the overall energy balance in the intracluster medium. The reason for the preservation of the relic radio bubbles may be found in the magnetic fields that permeate the ICM. It has been known for some time that the hot gas in clusters of galaxies often has within it a significant magnetic field (e.g., Carilli & Taylor 2002; Taylor et al. 2002), with typical magnetic field strengths of order 5×10^{-6} G. The origins of such fields remain somewhat obscure, but their effects on the intracluster medium are significant. As a radio source near the cluster center begins to inflate a cavity in the hot ICM, the ambient magnetic field is excluded from this cavity along with the hot intracluster gas. This will result in the external field forming a sheath around the cavity in which the field is primarily tangential to the cavity surface and has a higher value than the ambient field due to the effects of compression, as can be seen from simple flux conservation arguments. As mentioned above, the X-ray data imply that the cavity expands subsonically or transsonically, and thus this region of compressed and largely azimuthal field will expand into the ambient ICM at the local signal speed, slightly ahead of the advancing boundary of the inflating cavity.

This layer of tangential magnetic field around the buoyant cavity will suppress the short wavelength and fastest growing modes of the Rayleigh-Taylor (R-T) and Kelvin-Helmholtz (K-H) instabilities. Because the lifting and mixing of different layers of the ICM is mediated primarily by the R-T instability, as is large-scale mixing of the energetic radio emitting plasma with the ICM, the presence of this external layer of magnetic field will have an important influence on the evolution of the buoyant radio cavities. A magnetic field parallel to the interface between two fluids of differing density will suppress the R-T instability because the field acts as a source of surface tension at the interface and thus stabilizes small wavelength perturbations. This stabilization occurs for all wavenumbers larger than (e.g., Chandrasekhar 1961; Shore 1992)

$$k_c = \frac{2\pi g(\rho_2 - \rho_1)}{B^2 Cos^2\theta}\,, \tag{1}$$

where g is the acceleration due to gravity, ρ_1 is the lighter fluid (the radio bubble) and θ is the angle between the magnetic field vector and the wave vector of the perturbation. For a tangled azimuthal field and average value of $\cos^2\theta = 1/2$ can be used. The value of k_c provides the wavenumber of marginal stability, and formally the growth rate of this mode is zero. Perturbations of longer wavelength grow initially at a rate given by

$$n^2 = \frac{gk}{(\rho_2 + \rho_1)}[(\rho_2 - \rho_1) - \frac{kB^2 cos^2\theta}{2\pi g}]\,, \tag{2}$$

where n is the coefficient in the initial growth rate given by $\exp nt$. The wavenumber with the most rapid growth rate is found by differentiating Eq. 2 with respect to k.

A conservative estimate that produces the largest value of k_c and the fastest growth rate is to assume that $\rho_2 \gg \rho_1$. For the relic bubbles in A2597 and Perseus the ambient number densities are of order 10^{-2} cm^{-3} at distances of $\sim$ 30 kpc from the cluster center, which is the appropriate distance for these relic radio bubbles. Using the gravitational potential of a central galaxy of mass 10^{12} solar masses and an average value of the magnetic field of 5×10^{-6} G, which assumes no amplification of the field in the compressed sheath surrounding the bubble and which will maximize the value of k_c, one finds $k_c = 1.37 \times 10^{-22}$, or

$$\lambda_c = 2\pi/k_c = 15.2\,\mathrm{kpc}\,.$$

This is the shortest wavelength for the onset of the R-T instability under these conditions. The wavenumber of the fastest growing mode in the linear regime, obtained via differentiation of Eq. 2, is $k_* = k_c/\sqrt{3}$, and substitution of this into Eq. 2 gives the maximum growth rate as

$$\Gamma_* = 1/n_* = 4.2 \times 10^7\,\mathrm{yr}\,.$$

This is the time required for an initial perturbation of wavelength λ_* to grow by a factor of e; subsequent

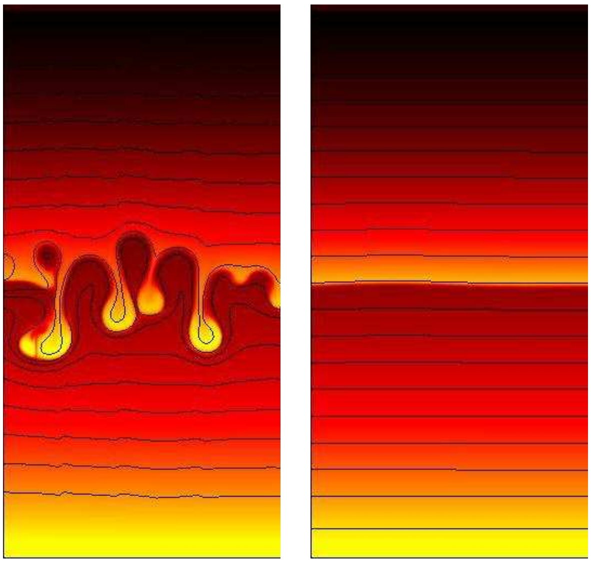

FIG. 1.— Density contours and field lines for a light plasma supporting a denser one. Left: $\beta = 1.3 \times 10^3$. Right: $\beta = 130$. The panels are 1 kpc wide, the plasma temperature is 10^7 K, and the time is 1.5×10^7 yr.

growth into the non-linear regime that will result in disruption of the radio cavity will require times greater than this by at least factors of two. This analytic result is confirmed by the use of numerical MHD calculations of the R-T instability (e.g., Ryu et al. 2000; Tregillis et al. 2001) that show the suppression of the instability for times in excess of 1.5×10^7 yr for plasma $\beta \simeq 10^2$, which is a value appropriate to the ICM. The results of such a calculation are shown in Figure 1.

The interface between the buoyant cavity and the ambient ICM is also subject to the Kelvin-Helmholtz (K-H) instability between two fluids in relative motion. Again, the effective surface tension of the tangential ICM field that surrounds the cavity can suppress the onset of this instability. In the absence of a gravitational restoring force perpendicular to the fluid interface, the flow is stable against the K-H instability if (e.g., Chandrasekhar 1961)

$$(U_1 - U_2)^2 \leq \frac{B^2(\rho_1 + \rho_2)}{2\pi\rho_1\rho_2}\,, \qquad (3)$$

where U_1 and U_2 are the velocities of the two fluids (in this case $U_2 = 0$ and $U_1 = U_{rel}$), B is the average value of the tangential magnetic field, and the densities ρ have the same meaning as previously. The Kelvin-Helmholtz instability is of less importance as an agent for mixing the intracluster medium with itself and with the hot radio source plasma than is the Rayleigh-Taylor instability. The K-H instability will, in its fully developed non-linear form, lead to a turbulent mixing layer along the surface of the radio source cavity (e.g., De Young 2002). This will influence a much smaller volume of the ICM than will the R-T instability that leads to the destruction and complete mixing of the radio source bubble with the ICM.

The relative speed of the buoyantly rising bubble is clearly subsonic; the three-dimensional simulations of Brüggen et al. (2002) show a relative speed of $\simeq 2.5 \times 10^7$ cm s^{-1}, and their analytic expression giving an order of magnitude estimate of the terminal speed of a rising bubble yields a similar value. (See also Churazov et al. 2001.) The same intracluster conditions as used in calculating the onset of the Rayleigh-Taylor instability gives stability against the K-H modes if $U_{rel} \leq 1.5 \times 10^7$ cm s^{-1}. These speeds are comparable to or greater than the relative speeds of the buoyantly rising bubbles obtained from the numerical simulations, and the interface is marginally stable against the Kelvin-Helmholtz instability. The growth rates of this instability are of order $n \approx kU_{rel}$, and for any appreciable mixing to occur (and for any observable deformation of the bubble interface) the wavelength of the instability should be of order 1 kpc or more. This then gives growth times of order 10^7 years or more.

2.2. *Implications for Re-energization of Cooling Flows*

Use of the buoyant speeds obtained from the simulations (Brüggen et al. 2002; Churazov et al. 2001) gives lifetimes for the relic radio bubbles in A2597 of 10^8 years and $\sim 5 \times 10^7$ years for those in A426. The three-dimensional hydrodynamic simulations of Brüggen et al. (2002) and the similar high resolution two-dimensional simulations of Brüggen & Kaiser (2002), which are of the appropriate scale and energy input for these objects, show that the rising cavities are clearly being disrupted at times of 3–4 $\times 10^7$ years at a distance of $\simeq$ 15 kpc for the three-dimensional case and at $\simeq 6 \times 10^7$ yr and $\simeq$ 20 kpc for the two-dimensional calculation. (The two dimensional case maybe more stable due to suppression of some 3-D modes.) However, the relic radio bubbles are still intact and show no signs of disruption at distances of 30 kpc and times of 10^8 years. Hence some additional processes other than purely hydrodynamical ones must be at work, and the above calculations show that the displaced intracluster magnetic field may provide the stabilizing influence that keeps the relic bubbles intact. The Rayleigh-Taylor instability, which is the most disruptive, does not even commence until times of about 5×10^7 years, and the *shortest* wavelength of the initial instability is $\simeq$ 15 kpc, which is comparable to the radii of the relic bubbles in A2597 and is comparable to the overall size of the bubbles in A426. Hence both the spatial and temporal scales for disruption of these relics are such that this process has not caused disruption by their current age. This then implies a significant reduction of the mixing of energetic radio source material with the ambient ICM, and in addition it implies a lowered efficiency in "lifting" one part of the ICM into another because the interface between the bubble and the ICM remains unperturbed.

Additional support for this result comes from the two-dimensional MHD calculations of Brüggen & Kaiser (2001). These calculations consider a scale much larger than that appropriate for the relic radio bubbles, with initial configurations extending from 200 to 400 kpc and with source energies more appropriate for FR-II radio sources than for the FR-I objects considered here. In addition these calculations do not consider the effects

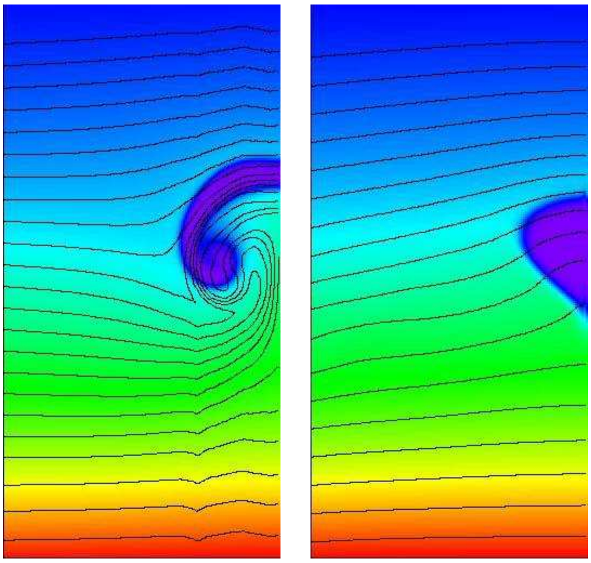

FIG. 2.— Density (greyscale) and field lines for a buoyantly rising bubble in an ICM with $T = 10^8$K. Left: $\beta = 1.2 \times 10^6$, time is 6.5×10^7 yr. Right: $\beta = 50$, time is 1.5×10^8 yr.

of the ambient magnetic field in the ICM, but when a circumferential field is placed around the radio bubble "by hand," the resulting geometry is similar to that seen in the relic radio bubbles. Moreover, this configuration shows no signs of disruption or mixing with the ICM. A self consistent 2-D MHD calculation using an advanced "TVD" code (e.g., Ryu et al. 2000; Tregillis et al. 2001) shows a similar result for plasma β of order 100 and a bubble size of $\simeq 10$ kpc initially. These results are shown in Figure 2. The above calculations for the onset of disruptive instabilities in the presence of the magnetic field in the ICM show that the transfer of energy from the radio bubbles to the intracluster medium may not be prompt, and that the effectiveness of such radio sources in reheating cooling flows may be less than originally suggested. The final stage of transfer of energy from a radio relic to the ICM takes place through the turbulent dissolution of the radio source and its ultimate transfer into heat. The time scale for this very non-linear process is calculated next.

2.3. *Turbulent Mixing of Radio source Debris and ICM Heating*

Once a radio bubble has been disrupted by the Rayleigh-Taylor instability, it develops large substructures which then break down into ever smaller eddies and cells. This process can be seen in the high resolution 2-D hydrodynamic simulations of Brüggen & Kaiser (2002), and it ultimately results in turbulent flow. The current numerical simulations do not follow the evolution of the flow into this regime (Brüggen et al. 2002). Though such flows contain very fine structure, they do not actually heat the ambient ICM until the turbulent cascade has proceeded down to scales corresponding to the dissipation region. A question of relevance to the reheating of the ICM is the time scale for this process to occur. Using the wavelengths of the initial instability found above, it is possible to calculate the development of fully non-linear MHD turbulence in three dimensions (e.g., Orszag 1970, De Young 1992). This calculation proceeds from continuous injection of energy at the instability wavelength and follows the development of a turbulent cascade through an inertial range and into the dissipation region. Once an equilibrium state has been established, heat is being injected into the ICM at the same rate as energy is being extracted from the dissolving radio relic. The time development of the turbulence spectrum from an initial delta function to an equilibrium spectrum is obtained after about 10 large scale eddy turnover times.

The connection to the relic radio bubbles is made by noting that the shortest wavelength for onset of the Rayleigh-Taylor instability is $\simeq 15$ kpc, and that the wavelength for the fastest growing mode is $\sqrt{3}$ times this. Using this as the scale of the large eddy injection region, and using an eddy rotation speed comparable to that of the speed of the rising radio bubbles from the hydrodynamic simulations (300 km s^{-1}) gives

$$\tau_{edd} = \lambda_{edd}/v_{edd} = 4.4 \times 10^7 \,\text{yr}\,. \tag{4}$$

This then implies that once the instability begins, the actual heating of the ICM commences about 4×10^8 years later. Hence this calculation, when coupled with the calculation for the onset of the Rayleigh-Taylor instability in the presence of the displaced ICM magnetic field, shows that the transformation of radio source energy into heat input to the ICM may not take place until about 5×10^8 years after the initial formation of the buoyant radio source bubble.

Sincere thanks are due to Tom Jones for his extensive advice and assistance in running the TVD MHD code.

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