Relic Radio “Bubbles” and Cluster Cooling Flows

David S. De Young

1 National Optical Astronomy Observatory, Tucson, AZ, USA

Accepted for publication - MNRAS

ABSTRACT
Recent suggestions that buoyant radio emitting cavities in the intracluster medium can cause significant reheating of cooling flows are re-examined when the effects of the intracluster magnetic field are included. Expansion of the cavity creates a tangential field in the ICM surrounding the cavity, and this field can suppress instabilities that mix the ICM and the radio source. Onset of instability can be delayed for \( \sim 10^8 \) yr, and calculation of the subsequent turbulent cascade shows that actual reheating of the ICM may be delayed for up to \( \sim 5 \times 10^8 \) yr. These results may explain why the relic radio cavities remain as intact entities at times \( \geq 10^8 \) yr, and the delay in injection of energy from the radio source into the intracluster medium may mean that the role of radio sources in reheating cooling flows should be re-examined. In addition, the existence of relic radio cavities may also imply that the particle content of radio source lobes is primarily electrons and protons rather than electrons and positrons.

Key words: galaxies:clusters - cooling flows - galaxies:active - radio sources

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 early hints of this came from the Einstein Observatory x-ray observations of Cygnus A (Harris et al. 1994). Unmistakable evidence for interaction came from the ROSAT high resolution images of NGC 1275 in the Perseus cluster (Böhringer et al. 1993), and 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 and spheroidal 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). In addition, the x-ray observations of the cavity in A2597 show that the pressure in the limb brightened region surrounding the cavity is not higher than the ambient ICM pressure, but that it is comparable to or somewhat lower than the ambient value (McNamara 2002a, McNamara et al. 2001). The densities in the limb brightened region are, however, higher than that in the undisturbed ICM. This is not what would be expected if the surface of the cavity were expanding supersonically into the ICM, since the resulting shock in front of the cavity surface would yield a pressure significantly higher than ambient: \( p_1/p_0 = (2\gamma M^2_F - \gamma + 1)/(\gamma + 1) \), where \( M_F > 1 \) is the Mach number of the shock relative to the ambient gas, the subscripts 0 and 1 refer to pre- and post- shock conditions, and \( \gamma \) is the usual ratio of specific heats. The above relation is valid for arbitrary shock strengths (e.g., De Young 2002). Moreover, the geometry of the cavities, and especially the “relic” cavities discussed below, is not suggestive of the supersonic expansion that would be expected for a radio lobe that is still being supplied by collimated jets emanating from the nucleus of the parent galaxy. As is well known, these energetic lobes have a much more elongated geometry, such as that seen in the “classical” FR-II radio sources. The nearly spherical geometry of the x-ray and radio morphologies under discussion here is consistent with a radio lobe that has come into rough pressure equilibrium with the ambient medium. Again, this is particularly true of the relic cavities discussed below, where there is no clear connection seen in radio emission between the relic and the active nucleus. In addition, the inner radio source in A2597 shows a complex and contorted geometry that suggests that strong deceleration and “frustration” may be taking place in the inner regions where the extended source is still being fed by outflow from the nucleus. This again would lead to prompt deceleration of the radio source relative to the ICM, and when the outflow from the nucleus ceases, such objects would rapidly come into pressure equilibrium with...
the ambient gas. All of this is suggestive of rather 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). It is important to note that all the above arguments about the expansion speed of the relics into the ICM are indirect. Since no expansion speeds can be measured, it is possible that the expansion of these objects is still supersonic, in excess of $10^8$ cm s$^{-1}$, in which case their internal energies are even higher than if they were in pressure equilibrium. In addressing this issue, Soker, Blanton & Sarazin (2002) argue that certain combinations of effects can result in a mildly supersonic expansion producing x-ray signatures that are consistent with the data, though strong shocks appear to be ruled out. The consequences of possible supersonic expansion will be discussed subsequently.

### 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 with a geometry similar to that seen in the x-ray data is produced by these simulations. This may be due in part to the effects of the axisymmetry constraint. 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. The two dimensional very high resolution hydrodynamic simulations of Brüggen and Kaiser (2002) show very clearly the onset and non-linear development of surface instabilities in the rising cavity, and these elegant 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 could be even more effective due to the larger number of modes available for the development of the instability, (assuming that the resolution of the numerical simulation is unchanged). 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 (A126) and A2597 clusters, though other examples have also been found (McNamara 2002b). These relic bubbles are coherent objects that are nearly spherical in appearance and have nearly featureless 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 may imply the need for electron re-energization (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 possibly 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 $5 \times 10^{-6}$ G. The origins of such fields remain somewhat obscure, but their effects on the evolution of radio sources in clusters 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 these instabilities, 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)

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

where $g$ is the acceleration due to gravity, $\rho_1$ is the density of the lighter fluid (the radio bubble) and $\theta$ is the angle between the magnetic field vector and the wave vector of the perturbation. For a tangled azimuthal field an 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

$$n^2 = \frac{g k}{(\rho_2 + \rho_1)} \left[ (\rho_2 - \rho_1) - \frac{k B^2 \cos^2 \theta}{2\pi g} \right], \quad (2)$$

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 $k$. Note that the instability treated here is that of the surface of a buoyant rising in a gravitational field and not that of the surface of a decelerating expansion. It is assumed here that the radio relics are in approximate pressure equilibrium with the ambient gas. If the relics are expanding supersonically then this will not be the case, but the age of these relics and their disconnection from the active nucleus, together with their geometry, strongly suggests that they have come into approximate equilibrium with their surroundings. The non-relic radio bubbles in the inner regions may be expanding at a mildly supersonic rate, as mentioned in Introduction, and such supersonic propagation speeds can act to suppress the R-T instability in those objects.

A conservative estimate that produces the largest value of $k_c$ and the fastest growth rate is that $\rho_2 \gg \rho_1$. For the relics in A2597 and Perseus the ambient number densities are of order $10^{-2} \text{ cm}^{-3}$ at distances of $\sim 30 \text{ kpc}$ from the cluster center, which is the appropriate distance for these relic radio bubbles. Using the gravitational potential of a central galaxy of mass $10^{12} \text{ solar masses}$ and an average value of the magnetic field appropriate for cooling flow clusters of $5 \times 10^{-8} \mu G$ (e.g., Carrill & Taylor 2002), which assumes no significant amplification of the field in the compressed sheath surrounding the bubble and which will maximize the value of $k_c$, one finds $k_c = 1.37 \times 10^{-22} \text{ cm}^{-1}$, or

$$\lambda_c = 2\pi/k_c = 15.2 \text{ kpc}.$$ 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 $k_\ast = k_c/\sqrt{3}$, and substitution of this into Eq. 2 gives the maximum growth rate as

$$\Gamma_\ast = 1/n_\ast = 4.2 \times 10^7 \text{ yr}.$$ This is the time required for an initial perturbation of wavelength $\lambda_\ast$ to grow by a factor of $e$; subsequent 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.

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, which is the case here, the flow is stable against the K-H instability if (e.g., Chandrasekhar 1961)

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

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 $\rho$ have the same meaning as previously. The Kelvin-Helmholtz stability 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. This is because 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 ratio of these two volumes is of order $V_{K-H}/V_{R-T} \sim \Delta R/R$, where $R$ is the radius of the bubble and $\Delta R \ll R$ is the thickness of the turbulent mixing layer.

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 $\sim 2.5 \times 10^7 \text{ cm s}^{-1}$, and their analytic estimate of the terminal speed of a rising bubble yields a similar value. (See also Churazov et al. 2001.) Equation 3 actually applies to the case where the same magnetic field exists on both sides of the interface. The stability criterion basically states that if the relative speed of the two flows is less than the Alfvén speed, then the Kelvin-Helmholtz modes are stabilized, since perturbations are then damped by the fast moving Alfvén waves moving along the interface. For the case of the relic radio bubbles the magnetic
field is different inside and outside the interface, and hence the relevant Alfvén speed for the two different regions must be used. In the exterior, the same intracluster conditions as used in calculating the onset of the Rayleigh-Taylor instability gives stability against the K-H modes if \( U_{\text{rel}} \ll 1.5 \times 10^7 \) cm s\(^{-1}\). For the interior the conditions are less well known; pressure equilibrium plus the lack of x-ray emission in the Chandra band pass suggests the presence of a hot and rarified gas, and if the interior number density is of order 10\(^{-4}\)

(cf. Sect. 3) and the magnetic fields are near the equipartition values of a few \( \mu \)G, then again stability against K-H modes occurs for \( U_{\text{rel}} \leq 3 \times 10^7 \) cm s\(^{-1}\). Thus 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 \( n \approx k U_{\text{rel}} \), 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\(^7\) 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 for these objects, show that the rising cavities are clearly being disrupted at times of \( \sim 3 \times 10^7 \) years at a distance from the nucleus of \( \sim 15 \) kpc for the three dimensional case and at \( \sim 6 \times 10^7 \) yr and \( \sim 20 \) kpc for the two dimensional calculation. (The two dimensional case has a higher energy input than is appropriate for these cluster radio sources, and it also may be 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 ages 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. In this case the Rayleigh-Taylor instability, which is the most disruptive, does not even commence its growth in the small amplitude linear phase until times of about 5 \times 10^7 years, and the shortest wavelength of the initial instability is \( \sim 15 \) 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. This is to be compared with the purely hydrodynamic simulations, which show that the R-T instability has proceeded far beyond the linear scale at times of \( 5 \times 10^7 \) years, and at wavelengths that are much less than the overall radius of the rising bubble. Hence both the spatial and temporal scales for disruption of these relics in the presence of external magnetic fields are such that this instability 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 may imply a lowered efficiency in "lifting" one part of the ICM into another. This is because, in the purely hydrodynamic case, the "lifting" is due to boundary layer (as opposed to mixing layer) effects, and the unperturbed surface of the bubble has both a thinner boundary layer than a surface roughened by small wavelength instabilities and a smaller total surface area than that of a fully perturbed surface that is deformed by large wavelength instabilities. However, in the MHD case the presence of external magnetic fields may actually increase the drag on the bubble, and hence its lifting effect, because of the long range nature of the fields. A self consistent MHD calculation is required to determine the magnitude of this effect.

Additional support for magnetic stabilization comes from the two-dimensional MHD calculations of Brüggen and 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 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. It is important to note that this calculation of Brüggen and Kaiser employs a magnetic field strength that has an energy density of 10 percent of that of the thermal energy in the ambient ICM (their "weak field" case). While this field is dynamically unimportant, it is stronger than the cluster magnetic fields used here. However, the results are clearly indicative of the effects of tangential magnetic fields around a radio source bubble. The obvious next step is a self-consistent three dimensional MHD calculation that includes the ambient magnetic field in the intracluster medium, and this is underway. However, 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). The method employed solves the time dependent MHD equations in their non-linear form, and the use of Fourier transformed second order moments of velocity and magnetic field allows a calculation of the time evolution of both kinetic and magnetic energy over many orders of magnitude in spatial resolution. A wide variety of initial and boundary conditions can be accommodated, and details of the method of calculation, including the energy transfer among different wavenumbers and the closure relations and dissipation scales, can be found in the above references.

The calculation here begins with continuous injection of energy at a single wavelength, which is the wavelength of the most unstable and fastest growing mode calculated in Sect 2.1. Energy injected at this scale quickly causes perturbations of the flow at smaller scales, and this causes the development of a turbulent cascade of energy to ever smaller scales or larger wavenumbers. The multiple interactions among turbulent eddies on different scales results in the creation of a steady state turbulent flow with a loss free propagation of energy through an inertial range into a dissipation scale. The calculation assumes that the magnetic field is homogeneous and weakly isotropic (allows helicity), since the non-linear stage of the R-T instability, once established, will disrupt the original tangential field and advect it with the large scale eddies as they rotate. Equipartition of the turbulent magnetic field with the kinetic energy will occur only on the smallest scales. If for any reason the large scale tangential field persists, it will inhibit the turbulent cascade and increase the time required for the turbulent energy to be injected as heat into the intracluster medium. 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. Figure 1 shows the results of such a calculation in dimensionless form. The time development of the turbulence spectrum from an initial delta function injection of energy at \( k = 1 \) is clearly seen, and it is also clear that an equilibrium spectrum is obtained after about 10 large scale eddy turnover times. (Figure 1 shows the spectrum of turbulent kinetic energy; the spectrum of the turbulent magnetic energy is similar for wavenumbers about 10 large scale eddy turnover times. (Figure 1 shows the eddy turnover time at \( t = 1 \); C: \( t = 2 \); D: \( t = 5 \); E: curves for \( t = 10, 15, 20 \times 30 \).

The connection to the relic radio bubbles is made by noting that the shortest wavelength for onset of the Rayleigh-Taylor instability is \( \approx 15 \) 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

\[
\tau_{\text{edd}} = \frac{\lambda_{\text{edd}}}{v_{\text{edd}}} = 4.4 \times 10^7 \text{ yr}.
\]

This provides the scaling factor for the scale free result shown in Figure 1, and it then implies that once the instability begins, the actual heating of the ICM commences about \( 4 \times 10^8 \) years later. The calculation shown in Figure 1 does not extend to the actual dissipation range, which lies at much smaller scales than considered in the figure. However, extension of the turbulent spectrum to the dissipation range will occur on times much smaller than the time required to establish equilibrium over the range shown due to the much more rapid turnover time of the small scale turbulent cells. 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 \( 5 \times 10^7 \) years after the initial formation of the buoyant radio source bubble. This is a time comparable to the cooling time in the central regions of rich clusters (e.g., Fabian 1994), and hence the overall energy balance between cooling of the ICM and possible reheating due to the energy injected from radio sources may need to be reconsidered.

As mentioned at the end of Section 1, once the energy is placed into the ICM as heat, it must be distributed throughout the ICM if it is to have a global effect on the cooling flows in clusters, and Brüggen & Kaiser (2002) estimated this effect via an averaging calculation. This global dissipation and mixing will take additional time, presumably comparable to the orbital periods of the galaxies in the cluster in the absence of large scale ICM motions due to subcluster mergers. However, it is possible that local injection of heat can have a significant effect on the cooling flow phenomenon because local injection of heat can result in convective turnover being induced in the ICM on scales comparable to that of the relic and now virtually destroyed radio bubble. This convective activity can serve to mix hotter and cooler regions of the ICM, and if multiple events such as this were to occur, an overall effect on the cooling flow could result. The timescale for this to take place, together with its spatial extent, must be determined by a numerical calculation, but \( 5 \times 10^8 \) years seems an appropriate lower limit, since the convection begins as soon as heating commences.

2.4 Relation to Other Radio "Relics" in Clusters

Diffuse radio emission from clusters of galaxies has been observed in many clusters (e.g., Carilli & Taylor 2002), and in some cases the radio morphology of this emission is suggestive of that seen in FR-I or FR-II radio sources, even though
a parent galaxy cannot be clearly identified. Recent high resolution observations of four of these possible “relics” (Slee et al. 2001) show very extended, diffuse and filamentary morphologies. This appearance is very different from the relic radio bubbles considered here, and the sources observed by Slee et al. do not have clear and unambiguous identifications of the parent galaxies. The radio morphologies are suggestive of much later stages of evolution of radio relics, possibly under the influence of large-scale shearing motions in the intracluster medium. Kaiser & Cotter (2002) have modeled these objects as relics of FR-II radio sources. Though FR-II objects are not commonly seen in rich clusters, if these are in fact FR-II remnants then their evolutionary tracks may be different than those of the lower powered relic radio bubbles considered here. In any case, it is interesting that even these sources do not appear to have been completely assimilated into the ambient ICM, even at the ages of greater than 10^8 years considered by Kaiser & Cotter. This suggests again that the magnetic fields in both the ICM and in the radio relics naturally inhibit the complete mixing of the radio source with its environment, at least at some level. Calculation of the transfer of energy from the radio source to the ambient ICM for these large sources and at late times would be of interest in relation to cluster cooling flows.

3 IMPLICATIONS FOR THE PARTICLE CONTENT OF RADIO SOURCES

A long standing issue in understanding extragalactic radio sources is that of the nature of the energetic particle populations contained within these objects (e.g., De Young 2002). While relativistic electrons are clearly present, the nature of the neutralizing particles, whether protons or positrons, is still under debate. The relic radio bubbles appear to be in pressure equilibrium with the hot ICM, yet they do not emit x-rays at the same intensity or energy as does the ambient medium. The question then arises as to the nature of the material in the bubble that contributes the required energy density; it could be magnetic field, hot protons, or very hot positrons. Hot positrons could arise from the very low energy tail of a power-law distribution of electrons and positrons. If so, care has to be taken in choosing the low energy cutoff of such a distribution; it must supply the required pressure, but it must not be such that the electrons and positrons, themselves subject to Bremsstrahlung, will emit x-rays above the observed limits. For example, if a mildly relativistic electron-positron population is used with γ ≳ 1, as has been suggested for some compact electron-positron jets (e.g., Celotti & Fabian 1993), then pressure equilibrium with the surrounding ICM at p ≳ 10^{-16} dyn cm^{-2} will give rise to a Bremsstrahlung emissivity per unit volume from both electrons and positrons that is roughly 10 percent of the radiation from the ambient ICM. This emission should lie within the sensitivity limits of the Chandra Observatory HRC but at the upper end of its energy bandpass.

An insight into this issue may arise from the possible need to reaccelerate the synchrotron emitting electron populations in the relic radio bubbles. The dynamic lifetimes are in excess of the radiative lifetimes (e.g., McNamara et al. 2001), and the requirement for reacceleration also emerges from the calculation of synchrotron radiation expected from the hydrodynamical simulations (Brüggen et al. 2002). Under the assumption that reacceleration is the relevant process, and if such reacceleration is to take place through internal shocks, Fermi acceleration, or turbulent acceleration via stochastic processes, then the fluid within the bubble must be able to sustain such motions and density inhomogeneities for a time long enough to provide significant reacceleration. If this fluid is an electron-positron gas, and if it provides enough internal energy to be in pressure balance with the hot external ICM, then this fluid is mildly relativistic. Such a hot gas has high sound speeds, and as a result it will rapidly damp any discontinuities that produce shocks and will also not sustain large density or pressure inhomogeneities for significant times; i.e., for times in excess of many sound crossing times across the inhomogeneities. The exception to this is if significant cooling can be made to take place in density inhomogeneities, but in that case such areas would be extremely bright in x-rays. Hence it seems less likely that an electron-positron gas can both provide pressure equilibrium in the relic radio bubbles and also sustain the needed reacceleration of the radio emitting electron population. This is not the case for a electron-proton gas, which can be hot but not relativistic (\( T \sim 10^{10} \) K) and rarefied (\( n \sim 10^{-4} \)). This fluid will have low x-ray emissivity in the observed pass bands and will be in pressure equilibrium with the surrounding ICM. In this context it is interesting to note that thermalization of a mildly relativistic jet (\( v_j \approx 0.03c \)) through a termination shock at the ”working surface” will result in a temperature of \( 10^{12} \) K. Would such reacceleration processes produce observable inhomogeneities in the radio emission from the relic bubbles? As mentioned above, the emission seems homogeneous within the constraints of the low frequency observations. Inhomogeneities in emission would be expected if very large scale shock structures, comparable in size to the radio bubble, were present, but such structures would not be expected in an aged radio relic. A much more likely process is turbulent reacceleration, and this would occur more uniformly throughout the radio source volume on a ”fine grained” scale. Thus it would be unlikely to produce large scale intensity variations in the radio emission. (An alternative to reacceleration is that of ”storage” of energetic particles in regions of low magnetic field, with radiative losses taking place only in high field regions in an inhomogeneous magnetic field distribution. This process has been suggested as a mechanism for larger FR-II and FR-I radio sources (e.g., Eilek, Melrose & Walker 1997, Tribble 1994), and though it cannot be ruled out here, the radio emission from the relic radio bubbles does not display inhomogeneities or filamentary structures on the scale resolved by current radio data.)

If this reacceleration process is taking place as described, it implies that the electron-proton gas was present in the radio source at early times, since the very existence of the well defined and undisrupted relic radio bubbles implies that there has been no significant mixing with the ICM, and that magnetic fields have kept the internal and external fluids separated from the time of creation of the radio source cavity. This would imply that the electron-proton gas was either ejected from the nucleus of the parent galaxy or that the protons were entrained into the outflowing jet as it passed through the parent galaxy’s interstellar medium. If magnetic isolation also exists in the outwardly moving jet
Relic Radio Bubbles and Cluster Cooling Flows

4 CONCLUSIONS

Recent observations of relic radio “bubbles” in the central regions of rich clusters imply that the lifetime of these objects is longer than that obtained from calculations of bubble disruption via the onset and development of hydrodynamic Rayleigh-Taylor and Kelvin-Helmholtz instabilities. Inclusion of the effects of the magnetic field in the ambient intracluster medium indicates that the creation of a tangential field on the surface of these bubbles as they expand can stabilize them against such instabilities for times comparable to their current lifetime. Calculation of the time of onset of instability under these conditions, together with calculation of the time required for the energy in the radio source to be dissipated as heat in the ICM, suggests that significant reheating of the ICM by radio sources may not commence until about $5 \times 10^8$ years after the creation of the radio source. As this time is comparable to the cooling times in the centers of rich clusters, the role of radio sources as a means of reheating cooling flows may be more complex than earlier thought. Finally, the existence of relic radio bubbles, together with their likely pressure equilibrium with the surrounding intracluster medium, can be used to argue for the presence of a hot gas interior to the bubbles that is composed primarily of electrons and protons rather than electrons and positrons. The isolating effects of magnetic fields interior and exterior to the radio bubbles then suggests that the particle content of the original radio jet as it emerged from the parent galaxy was primarily electrons and protons.

I thank Brian McNamara for many useful discussions and a referee for helpful comments.

REFERENCES

Böhringer, H., Voges, W., Fabian, A.C., Edge, A.C., Neumann, D.M., 1993, MNRAS, 264, L25
Brüggen, M., Kaiser, C., 2001, MNRAS, 325, 676
Brüggen, M., Kaiser, C., 2002, Nature, 418, 301
Brüggen, M., Kaiser, C., Churazov, E., Enßlin, T., 2002, MNRAS, 331, 545
Carilli, C.L., Taylor, G.B., 2002, Ann Rev Ast & Ap, 40, 319
Celotti, A., Fabian, A.C., 1993, MNRAS, 264, 228
Chandrasekhar, S. 1961, Hydrodynamic and Hydromagnetic Stability. Oxford, Clarendon Press, Ch 10
Churazov, E., Brüggen, M., Kaiser, C., Böhringer, H., Forman, W., 2001, ApJ, 554, 261
De Young, D.S., 1992, ApJ, 386, 464
De Young, D.S., 2002, The Physics of Extragalactic Radio Sources. University of Chicago Press, Chicago
Eilek, J.A., Melrose, D.B., Walker, M.A., 1997, ApJ, 483, 282
Fabian, A.C., 1994, Ann Rev Ast & Ap, 32, 277
Fabian, A.C. et al., 2000, MNRAS, 318, L65

Fabian, A.C., Celotti, A., Blundell, K.M., Kassim, N.E., Perley, R.A., 2002 MNRAS, 331, 369
Harris, D.E., Carilli, C., Perley, R.A., 1994, Nature, 367, 713
Kaiser, C.R., Cotter, G., 2002, MNRAS, 336, 649
McNamara, B.R., 2002a, in ”X-Rays at Sharp Focus”, eds. S.Vrtilek, E. Schlegel, ASP Conf. Series, Vol 262, p351
McNamara, B.R., 2002b, private communication.
McNamara, B.R. et al., 2001, ApJ, 562, L149
Nulsen, P.E.J., et al., 2002, ApJ, 568, 163
Orszag, S.A., 1970, J. Fl. Mech, 41, 363
Reynolds, C.S., Heinz, S., Begelman, M., 2002, MNRAS, 332, 271
Shore, S.N., 1992, An Introduction to Astrophysical Hydrodynamics. Academic Press, New York
Slee, O., Roy, A., Murgia, M., Andernach, H., Ehle, M. 2001, AJ, 122, 1172
Soker, N., Blanton, E. L., Sarazin, C.L., 2002, ApJ, 573, 533
Taylor, G.B., Fabian, A.C., Allen, S.W., 2002, MNRAS, 334, 769
Tribble, P.C., 1994, MNRAS, 269, 110