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Radio Galaxies in Cooling Cores

Jean A. Eilek

New Mexico Tech

A currently active radio galaxy sits at the center of almost every strong cooling core. What effect does it have on the cooling core? Could its effect be strong enough to offset the radiative cooling which should be occurring in these cores? In order to answer these questions we need to know how much energy the radio jet carries to the cooling core; but we have no way to measure the jet power directly. We therefore need to understand how the radio source evolves with time, and how it radiates, in order to use the data to determine the jet power. When some simple models are compared to the data, we learn that cluster-center radio galaxies probably are energetically important—but not necessarily dominant—in cooling cores.

1. Introduction

Cooling cores are clear observationally. They stand out dramatically from the general rich cluster population. They are, however, far from clear theoretically. With the advent of new data, the old arguments (where is the cooled gas? where is the evidence for flow?) have faded, but new ones have taken their place.

The new data are striking. Thanks to recent, high-quality X-ray spectra, we now know that there is simply not enough cool or cold gas to support the old cooling-flow models. We don't see the gas cooling through the intermediate temperature range that we would expect from the old models (e.g. Fabian 2004; Donahue 2004). Nor do we see the extensive reservoir of cold gas that the cooling-flow models predicted (although there definitely is some cold gas, e.g. Edge et al. 2002). Strong cooling cores are, indeed, a bit cooler than the rest of their clusters, but only by a factor of a few (Allen et al. 2001; DeGrandi & Molendi 2002). Given the short radiative lifetime of the cooling-core gas, something must be keeping it from cooling.

By looking at nearby cooling cores in the radio (from the VLA) as well as in X-ray (from *Chandra* and *ROSAT*), we also now know that central radio galaxies in cooling cores are interacting strongly with the plasma in the cooling core (Blanton 2004; Böhringer 2004). We also know that some cooling cores have high Faraday rotation, and thus that magnetic fields are probably important in the cooling-core plasma (Eilek & Owen 2002, or Taylor 2004; but see also Rudnick & Blundell 2003 for an alternative view). We are learning that cooling cores are complex places.

But the questions remain. Three issues seem timely.

- Why are cooling core clusters different? Is it more than happenstance that some clusters have unusually high central densities, but otherwise seem quite smooth and unperturbed?

- What controls the thermodynamics of cooling cores? Why is the temperature structure so regular, and what keeps the gas from cooling?

- How important are central radio galaxies to the cooling cores? Does every cooling core contain an important radio galaxy? Does the jet deposit enough energy in the local gas to be important in the thermodynamics of the core?

In this paper I will focus on the last issue, the role of radio galaxies. With an eye to the energetics of the cooling core, this issue can be broken up into two further questions:

- What is the jet power of the central radio galaxy over the lifetime of a typical cooling core?

- What fraction of that power is deposited in the gas of the cooling core?

In this paper I will only address the first question, which is complex enough by itself. I will leave the question of energy deposition to others. The place to begin is with the data. In §2 I demonstrate that almost every strong cooling core has a currently active radio source, and in §3 I point out that these cluster-center sources are atypical of the broader radio galaxy population. This is consistent with strong interactions disturbing both the radio source and the cooling core. But what is the jet power? Because it is not directly observable, we must consider how it affects what we can observe—the dynamics and radio power of the source. After setting the stage, in §4, I explore toy models (in §5 and §6, with important caveats in §7) which can connect the observables to the jet power. Finally in §8 I discuss what we can, or cannot, definitely say about the importance of radio jets in cooling cores.

2. Data: Radio Sources in Cooling Cores

We want to know how important cluster-center radio sources (CCRS) are to the energy budget of a "typical" cooling core. The first question to ask is how frequently the central galaxies in nearby cooling cores have active radio sources, and what are the radio powers of those sources. This should be answered statistically, rather than anecdotally, so we must consider complete samples of cooling cores. Two are available.

2.1. *Samples of Cooling Cores*

The first sample I take from the X-ray bright (flux-limited) sample from Peres et al. (1998). These authors used pointed *ROSAT* data for the brightest X-ray clusters in the sky. They carried out a deprojection analysis, and from that determined central cooling rates, cooling radii and "$\dot{M}$" mass inflow rates. I've taken the clusters from this set with $\dot{M} > 30 M_\odot$/year—these are the brightest, most centrally peaked clusters—and which are in the northern sky, to overlap with the sky coverage in the NVSS (Condon et al. 1998). This gives 30 clusters. Comparing this sample to the existing radio data—in the literature and using the NVSS—I find that the central galaxy in 25 of the 30 clusters has a currently active radio source, at or above a few mJy at 1.4 GHz.

The other sample I use is taken from the ROSAT All-Sky Survey (RASS) of 288 nearby Abell clusters, from Ledlow et al. (2003).The RASS is too photon-poor to allow for deprojection analysis, so Ledlow et al. (2003) formed aperture fluxes, quoting the 2–10 keV power within 62.5 kpc and 500 kpc of the cluster core. Cooling cores can be identified in this sample as those clusters which are X-ray bright and centrally concentrated. To form a sample for their VLA survey, Marković et al. (2004) select clusters with those properties, and which contain a massive central galaxy coincident with the X-ray peak. Using these criteria they find a set of 22 likely cooling-core clusters, which has 12 clusters in common with the Peres et al. (1998) sample. Checking the literature and the NVSS reveals, again, that most of these clusters have previously-known central radio galaxies. Marković et al. (2004) are following up on this with dedicated VLA studies of the set. They show that *all* of this sample (22/22) have a currently active central radio source.

This is an important result: almost every (and probably every) central galaxy in a cooling core hosts a currently-active CCRS. However, this is not necessarily due to the cooling core. Ledlow & Owen (1996) used optical and radio data on a complete sample of 188 radio sources in Abell clusters to form bivariate luminosity functions. They found that the brighter the parent galaxy, the greater the chance of it hosting a detectable radio source. Galaxies in their optically brightest subsample have a better than half chance of having an active AGN. Because the central galaxies in cooling cores are very bright and massive—well above L_*—it may be the galaxy, not its X-ray atmosphere, that causes the radio source to be active.

2.2. *Statistics: Relative Powers*

Thus, radio sources exist in essentially every strong cooling core. But how powerful are they? In order to compare radio and X-ray powers, we must be specific about definitions.

Many X-ray analysis papers, for instance the work by David et al. (1993) (from which Peres et al. 1998 take their total cluster powers) calculate the X-ray luminosity from the full cluster. This of necessity requires some assumptions about the underlying cluster structure, such as fitting β models to the cluster. On the other hand, Ledlow et al. (2003) take a more conservative approach, and quote the (directly measurable) flux within a 500 kpc aperture. I prefer the latter and use it in this paper; where necessary I convert the David et al. (1993) values to a 500 kpc aperture, using clusters in common in the two samples. Note that the Ledlow et al. (2003) fluxes are within 2-10 keV; an additional factor ~ 2 (David et al. 1993) will convert them to bolometric.

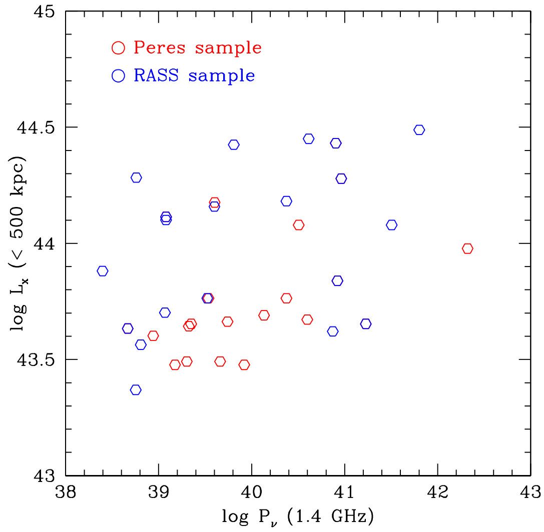

FIG. 1.— Radio power at 1.4 GHz vs. X-ray power between 2 and 10 keV from the central 500 kpc of the cluster, for both samples discussed in the text. Units on both axes are erg/s. No correlation can be seen: the large-scale X-ray power and the radio power of the central source do not know about each other.

The radio power also merits comment. Unlike X-ray telescopes, which sample a known spectrum over a broad frequency range, radio observations only measure one frequency at a time. Furthermore, we don't know the radio spectrum. Synchrotron emission is generally a power law but also shows curvature, and varies source to source. The radio spectrum is measured for some bright sources, but for most sources (including most of these samples) only the flux density, S_ν, at one frequency (1.4 GHz) is available. I therefore use "power at ν", $P_\nu = \nu S_\nu$, instead of the "bolometric" $P_{rad} = \int S_\nu d\nu$.

Our first quantitative result is that there is no correlation between the X-ray power (within 500 kpc aperture) and the radio power of the CCRS, as shown in Figure 1. This isn't surprising; the cluster is a big object and we wouldn't expect such a correlation.

However, because we're asking about the impact of the radio jet on the cooling region, we really want to consider X-ray powers of the cooling cores. Using the data in hand, we can define the "central region" in two ways. Peres et al. (1998) derive cooling radii, the radius within which the radiative cooling time is equal to the Hubble time. The cooling radii are ~100–200 kpc for this sample. The X-ray power within this region could be called the "cooling core" power, L_{cc}. Peres et al. (1998) point out that this is really a "maximal" cooling core, because the cluster may well not have remained undisturbed for the

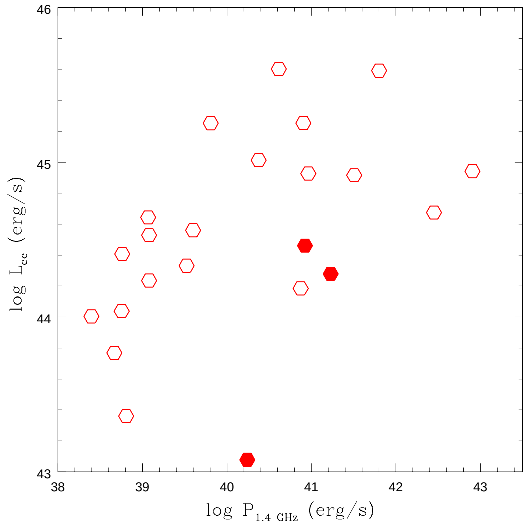

FIG. 2.— Radio power at 1.4 GHz plotted against the bolometric X-ray power within the classical cooling radius, from the deprojection analysis of Peres et al. (1998). This cooling radius, typically 100–200 kpc for this sample, was derived for a cluster age of 13 Gyr, and is therefore an upper limit to the likely cooling radius (as discussed in Peres et al. 1998). A modest correlation is apparent between the radio power and cooling-core X-ray power. The solid point at the bottom is M87, which is unusually radio-strong compared to its cooling core; the other two solid points are 3C317 in A2052, and 3C338 in A2199. All three of these sources are modeled in §6.

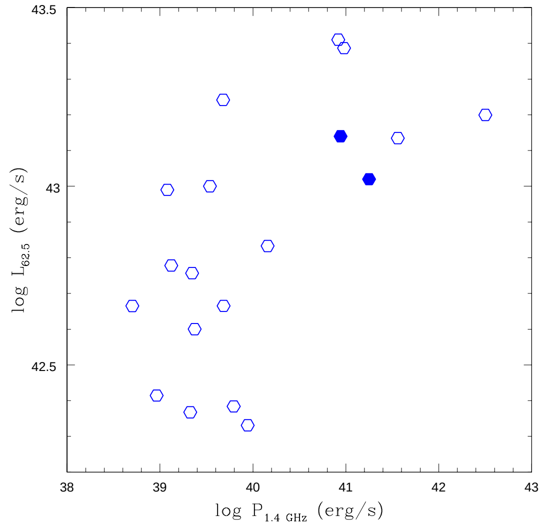

FIG. 3.— Radio power at 1.4 GHz plotted against the 2–10 keV X-ray power in the central 62.5 kpc, from Ledlow et al. (2003). A factor ~ 2 converts this to bolometric power (David et al. 1993). Once again, using this measure we find a correlation between the radio power and the central X-ray power. The X-ray aperture used here is typical of, or a bit greater than, the size of a well-developed cluster-center radio source. The two solid points are 3C317 in A2052, and 3C338 in A2199. (M87 is not included in this sample).

age of the universe.[1] Alternatively, Ledlow et al. (2003) give the X-ray power within 62.5 kpc, $L_{62.5}$, a scale which is smaller than most (maximal) cooling radii, but which matches the scales of the CCRS quite well.

Figures 2 and 3 compare the X-ray core power, using both definitions, to the single-frequency radio power. The story becomes more interesting when we consider only the central region. The radio power from the CCRS does show some correlation with the core X-ray power (Burns 1990 noted a similar trend for a different sample). This correlation may be telling us that the jet power knows about the large-scale cooling core environment (although just how is far from clear), or it may reflect the way in which the extended radio source reacts to the pressure in its surroundings.

The relative ranges of X-ray core power and radio source power will be useful for the modeling below. For the bolometric flux from the 62.5 kpc core, the range of powers is

$$\text{62.5 kpc cores}: \quad L_{62.5} \sim \left(10 - 10^4\right) P_\nu \,. \qquad (1)$$

The range of powers for the maximal cooling cores is

$$\text{maximal cooling cores}: \; L_{cc} \sim \left(300 - 3\times 10^5\right) P_\nu \,. \quad (2)$$

The range of radio power is much greater than the range of X-ray power; this could reflect either the range of intrinsic jet power, or the time evolution of the radio power (at a fixed jet power), or both.

[1] The relevant time scale, for instance, might better be the time since the last major merger in the cluster – that would give a smaller cooling radius and smaller L_{cc}.

2.3. *Summary: Radio Source Statistics*

The central galaxy in (almost) every strong cooling core contains an active galactic nucleus (AGN) and a currently active, jet-driven radio galaxy. The radio power of the CCRS is somewhat correlated with the X-ray power the cooling cores in which they sit, although the range of radio power is much greater than the range of X-ray core power. This may suggest that the strength of the cooling core has some connection to the jet power, but also that the radio power of a given source evolves significantly over the life of the source.

3. **Data: CCRS Are Different**

Radio sources in cooling cores are different from the general population of radio sources in galaxy clusters. This suggests that the special conditions in cooling cores impact the radio source therein. In order to understand how CCRS differ, we must review the general properties of radio galaxies.

3.1. *Radio Sources Throughout Clusters*

To understand the general nature of radio sources in the nearby universe, we can use the work of Owen & Ledlow (1997, and references therein), who present radio and optical data on ~ 250 radio sources in nearby Abell clusters. Study of their images reveals that the traditional Fanaroff-Riley Type I and Type II classifications are not the entire answer. Most radio galaxies in clusters are Type I in terms of their radio power and optical luminosity of the parent galaxy, but they show a great variety of morphologies and dynamics (Eilek et al. 2002). Nearly all of the resolvable Owen-Ledlow sources

FIG. 4.— A cartoon of the two types of radio galaxy commonly found in clusters. Almost all of the sources in the Owen-Ledlow cluster sample are one of these two types (or are too small to be resolved). The evolution of each is governed by directed momentum flux from the jet, as discussed in the text; the differences are probably due to internal fluid instabilities. Radio sources in cooling cores often do *not* resemble these types, but look more like the cartoon in Figure 7.

(about 3/4 of the total set) can be divided into two morphological groups, "tailed" and "straight", as illustrated by the cartoon in Figure 4. Only a few of the resolvable sources fit into neither category—and they are uniquely located in cooling cores (as discussed below).

Straight sources are created by directed jet flows, which continue more or less undisturbed from the galactic nucleus out to the end of the lobes. Straight sources comprise $\sim 1/5$ of the sample, and typically extend 30–150 kpc from the galactic core. This class includes a few classical doubles (Fanaroff-Riley Type II sources)—in which the jet remains very narrow and ends in a bright hot spot—but these are rare, only a dozen in the entire sample.

Tailed sources are also created by directed jet flows, but in these sources the jet is disturbed close to the galactic core. It broadens suddenly (usually), or gradually (occasionally), but does not fully disrupt; the flow continues on into the characteristic tails. These tails typically can be traced $\sim 50-300$ kpc from the galaxy; due to surface brightness decay their ends are often undetected. The dynamics of the tail flow are driven by a mix of momentum flux from the jet, buoyancy, and flows in the local intracluster medium (ICM). Tailed sources comprise $\sim 1/2$ of the Owen-Ledlow sample.

We have found no apparent environmental reason for these two types; their occurrence is not correlated with radio power or size, local ICM density, or magnitude of the parent galaxy. Eilek et al. (2002) speculate that the development, or not, of jet-disrupting instabilities is the important factor.

It should also be emphasized that FR Type II sources—the famous classical doubles—are rare in this sample, as they are in general in the nearby universe. This is unfortunate; even though they are the only type of radio galaxy that we understand well, they are *not* a good example for studying radio sources in clusters.

3.2. *Cluster-Center Radio Sources*

From the radio data for the two sets of cooling cores, we learn that CCRS are not typical of the general radio

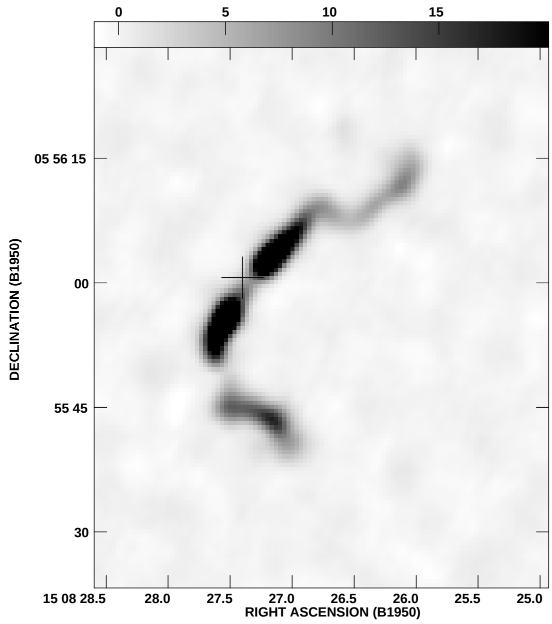

FIG. 5.— The central radio source in A2029, which is typical of the small, tailed radio galaxies found in cluster cores. The cross marks the position of the galactic core. 1.4 GHz VLA image from Owen & Ledlow (1997); see also Marković et al. (2004) who find that the tails are more extended and possible evidence of an underlying amorphous halo.

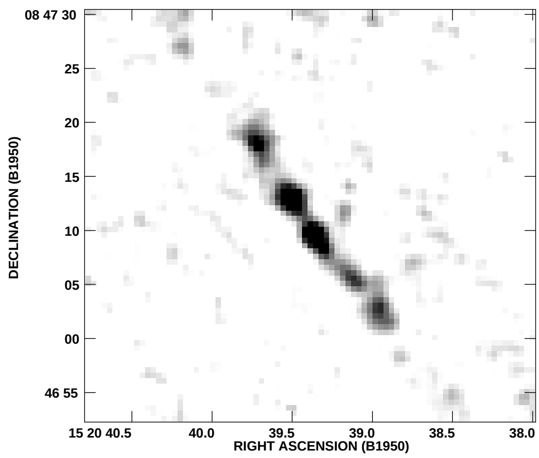

FIG. 6.— The central radio source in A2063, another of the small, tailed sources found in cluster cores. The source is symmetric about the galactic core, which is in the center of the image. 1.4 GHz VLA image from Owen & Ledlow (1997).

galaxy population. They differ in three important ways.

First, CCRS are morphologically different from the normal run of radio galaxies. Almost all CCRS large enough to be resolved with current data are either tailed sources, or unusual amorphous ones. (Cygnus A is the one exception, a FRII in a strong cooling core; Carilli et al. 1994). Figures 5 and 6 show typical small tailed sources. The amorphous sources (as sketched in Fig-

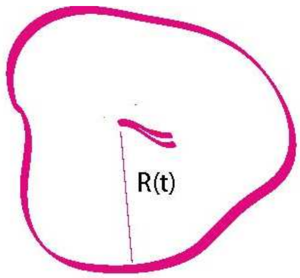

FIG. 7.— A cartoon of an amorphous, core-halo radio source; this morphology is common in cooling cores but rare elsewhere in the universe. The jet disrupts close to the core, and injects matter and energy to the radio bubble quasi-isotropically. $R(t)$ is the source radius, which grows with time; models of the source growth are discussed in §4.

ure 7) tend to have diffuse halos surrounding an active AGN core. Figures 8 through 12 show examples; 3C84 in the Perseus cluster (Fabian et al. 2002) is another well-known case. Based on current data, tailed and amorphous sources types occur about equally often in CCRS. However, there are hints that some small, tailed CCRS may be embedded in larger, faint halos (Marković et al. 2004), so that these unusual sources may be even more common. (Note that M87, figure 11, could appear as a tailed source if it were more distant and fainter.) In addition, *all* 5 of the amorphous sources in the Owen-Ledlow sample are in cooling cores, as are M87 and 3C84; these are very unlikely to be more normal sources seen in projection.

Second, CCRS tend to be smaller than most radio sources. With the sole exception of Hydra A (McNamara et al. 2000), the tails of which extend further than 300 kpc from the core, the detected extent of all other CCRS in both samples is less than 100 kpc, and most extend less than 50 kpc from the core. This may well be due to the higher ambient pressure in which the CCRS find themselves, which will slow down their spatial growth.

Third, CCRS tend to have steeper radio spectra than most radio sources (Ball et al. 1993, also Marković et al. 2004). Steep-spectrum radio emission is usually thought to mean the relativistic electrons have suffered significant synchrotron losses; but other interpretations, such as strongly inhomogeneous magnetic fields, are also possible.

3.3. *Summary: Cluster-Core Radio Sources*

The unusual nature of CCRS strongly suggests that something special in the cooling-core environment affects the growth and nature of the central radio source. The small size, and unusual morphology, hint that the cooling-core environment slows the growth of the source, and may fatally disrupt the jet very close to the AGN. The isotropized energy flow from the jet would create an amorphous halo, rather than a tailed radio source. The jet disruption by the local cooling-core plasma would also be expected to disturb and heat the plasma. This picture is, of course, consistent with the evidence from *Chandra* of strong interactions between the radio source and the plasma in some cooling cores.

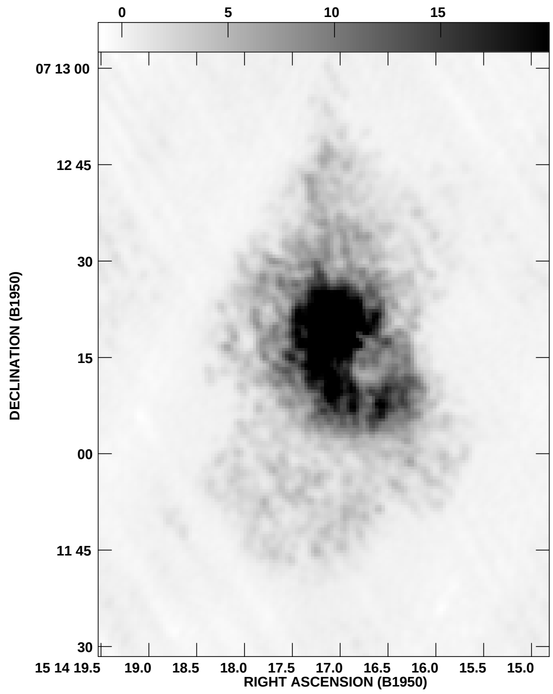

FIG. 8.— 3C317, the central radio source in A2052. The center of the galaxy coincides with the bright radio core, central in this image. VLA studies (Zhao et al. 1997) show that no radio jets exist past 200 pc, although VLB studies detect a 15 pc jet in the core. Thus, the jet is disrupted very close to the core and feeds a quasi-spherical "bubble" which is expanding into the plasma of the cluster core (Blanton et al. 2003). 1.4 GHz VLA image from Owen & Ledlow (1997); see also Marković et al. (2004) and Zhao et al. (1997) for other radio images.

4. **Interlude: The Jet Power**

We now know that radio sources are common, and probably universal, in the bright galaxies which sit centrally in cooling cores. We have strong evidence that CCRS are unusual, and are interacting strongly with the local ICM. This interaction must perturb the local ICM as well as disturb the radio galaxy; some amount of the jet energy must be deposited in the local ICM. What is not yet clear, however, is how important this interaction is to the energy budget of a "typical" cooling core.

In order to address this question we must determine the strength of the jet in a "typical" cooling-core AGN. The total energy flux in a radio jet of speed βc and cross section $S = \pi r^2$ is

$$P_j = \pi r^2 \gamma^2 \beta c \sum_{i,e} \left(\rho c^2 + 4p\right) + \frac{c}{4\pi} \int_S d\mathbf{s} \cdot \mathbf{E} \times \mathbf{B} \, . \quad (3)$$

In most usage, $\mathbf{E}$ is taken as the inductive field: $\mathbf{E} = -\mathbf{v} \times \mathbf{B}/c$. For later use, we can rewrite equation 3 as

$$P_j = P_{je} + P_{ji} + P_{jB} \, , \quad (4)$$

which generically represents the flux of relativistic electrons, ions, and magnetic field. We will see below, that the radio power measures P_{je}; the mean magnetic field in

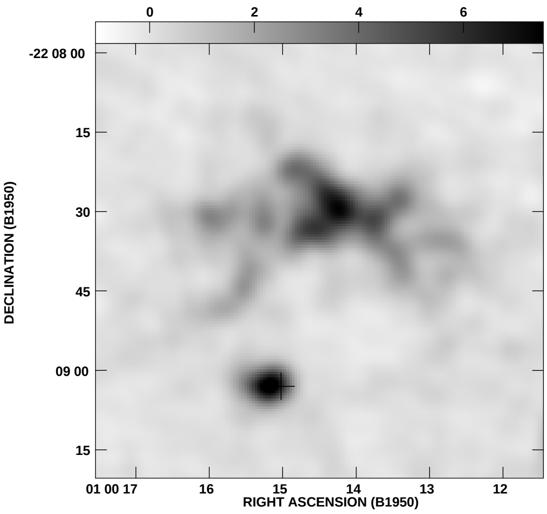

FIG. 9.— The central radio source in A133, one of the "amorphous" CCRS. The center of the galaxy coincides with the bright radio core to the south of the image. Although this fainter source cannot be imaged as deeply as A2052, both the radio morphology and the X-ray imaging (Fujita et al. 2002) suggest that this is also a "bubble"-like source, expanding into the cooling core of the cluster. 1.4 GHz VLA image from Owen & Ledlow (1997); see also Marković et al. (2004) for a deeper image, which establishes the connection between the galactic core and the halo to the north.

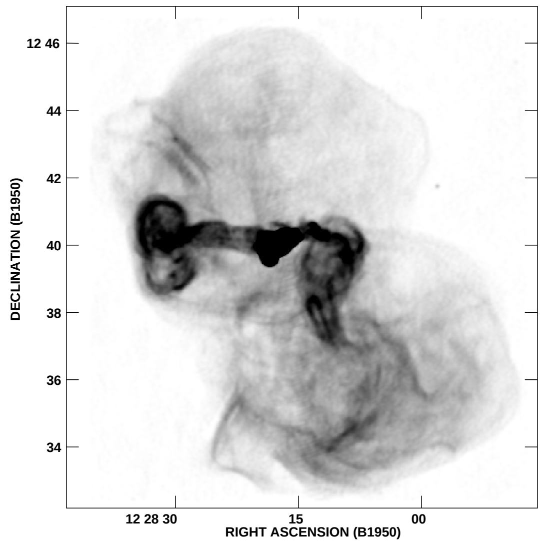

FIG. 11.— The prototypical "amorphous halo" source M87, in the core of the Virgo cluster. The halo extends $\sim$ 35 kpc from the galactic core. This high-quality image, from Owen, Eilek, & Kassim (2000), makes it clear that the inner jet disrupts within $\sim$ 2 kpc, but continues to feed plasma into the radio halo. Note that the "plumes", which extend from the core into the halo, are significantly brighter than the rest of the halo; if the source were further away, and fainter, only the plumes might be detected, and M87 would be identified as a tailed source.

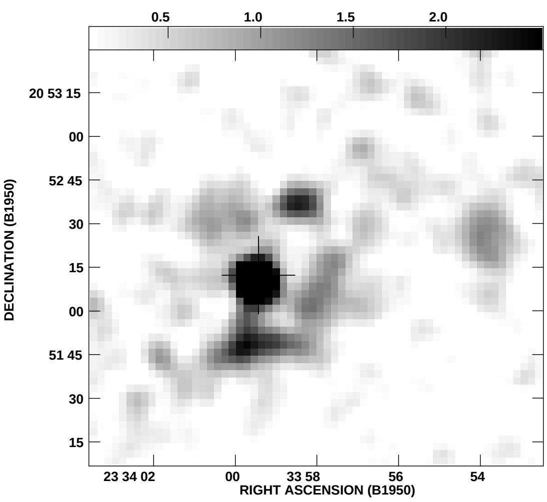

FIG. 10.— The central radio source in A2626, another of the amorphous CCRS. The center of the galaxy coincides with the central bright radio core; diffuse emission surrounds the core. 1.4 GHz VLA image from Owen & Ledlow (1997); see also Marković et al. (2004) for a deeper image.

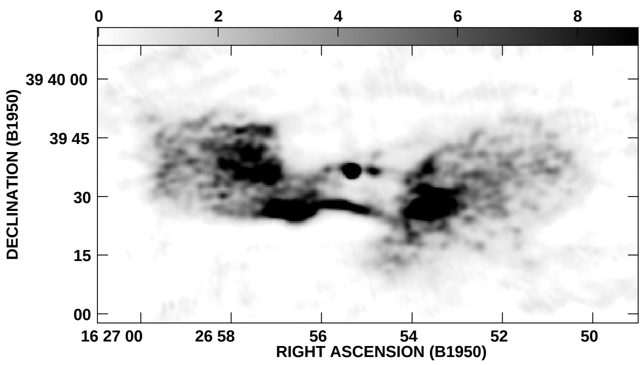

FIG. 12.— A2199, another unusual CCRS. The radio core – which coincides with the galactic nucleus, and which hosts a currently active two-sided VLB jet – is the bright spot in the center of the image. The X-ray image (Owen & Eilek 1998) makes it clear that the radio plasma and ICM are interacting strongly. The filament to the south, which appears jet-like, does not coincide with any feature in the galaxy. It's tempting to speculate that this source has been caught in the act of restarting, and that the southern filament is just a bright feature arising from "weather" in the radio plasma-ICM interaction. 1.4 GHz VLA image from Owen & Ledlow (1997).

the source at time t can be related to the ratio P_{jB}/P_j; and we have no *a priori* knowledge of the ion flux, P_{ji}.

The best way to determine P_j is of course to measure it directly. At present this is possible for only one source—M87—and only as a lower limit in that case (Owen, Eilek, & Kassim 2000). This jet is resolved, so we know its radius; proper motion studies find $\gamma \sim$ a few for bright features, and physical analysis tells us the flow speed is unlikely to be much slower than the feature speed (Hardee 2000). Finally, from standard synchrotron analysis, we know the *minimum* pressure in the jet; this is the lowest value of $p_B + p_e$ consistent with the observed radio emission.[2] For the M87 jet, these methods find $P_j \gtrsim$ few $\times 10^{44}$ erg/s. For comparison, the X-ray luminosity of the maximal cooling core $L_{cc} \sim 3 \times 10^{43}$ erg/s (Peres et al. 1998). Thus, this jet is clearly energetically important to the core of this cluster.

For other sources, we must use more indirect—and more model-dependent—methods. I discuss two in this paper. One method is to connect the radio power to the jet power. Because each source varies with time, this cannot be done for an individual source, but will have some statistical validity. Another method is to construct dynamical models of the source evolution, and from them connect the source size and internal energy to the jet power. Both of these methods require assumptions, in order to build the models; they must be checked, *post hoc*, for the validity of these assumptions. The two methods are also interconnected. Modeling the radio power requires knowledge of the source dynamics. Extracting the jet power from the source dynamics requires independent evidence of the age, which comes in principle from the radio spectrum.

In the rest of this paper I highlight the assumptions and general results of the models, focusing on what they can tell us about heating of cooling cores. Both models will be described in more detail in forthcoming papers (Eilek 2004).

5. Toy Models: Evolution of Radio Power

One first thinks of using the radio power to measure the jet power. We know the synchrotron power depends on relativistic electrons and magnetic field in the source. As the source evolves, so should the radio spectrum. Although the detailed plasma physics can be very complicated, it seems best to start with a simple model, and see what it predicts.

I therefore take the traditional approach to the relativistic electrons, namely, assuming that the jet injects new particles at a steady rate $q(\gamma)$ [normalized so that $P_{je} = \int q(\gamma)\gamma mc^2 d\gamma$]. If the electrons feel no further acceleration in the lobe, but simply lose energy at a rate $d\gamma/dt$, the electron distribution evolves as

$$\frac{\partial n(\gamma)}{\partial t} + \frac{\partial}{\partial \gamma}\left[n(\gamma)\frac{d\gamma}{dt}\right] = q(\gamma)\,. \tag{5}$$

I specify to synchrotron losses, $d\gamma/dt \propto \gamma^2 B(t)^2$. (Adiabatic losses are also important for young sources and low-γ particles, but synchrotron losses will soon dominate). Looking ahead to the dynamical models, I assume a magnetic field which slowly decays with time, $B(t) \propto t^{-1/6}$ (different decay rates change the details of the arguments below, but not the substance). Again following tradition, I assume that the jet injects a power law in the energy range $\gamma_o < \gamma < \gamma_m$. Solutions of equation 5 are straightforward (Eilek & Shore 1989), giving a broken power-law electron spectrum which steepens at a critical energy $\gamma_c(t) \propto 1/B^2 t \propto t^{-2/3}$. The low-$\gamma$ distribution mimics the injection spectrum, and the high-γ distribution steepens due to synchrotron losses.

5.1. *Solution: Radio Power of One Source*

To determine the radio spectrum, note that the electron energy which "maps" to the observing frequency ν is

$$\gamma(\nu) \propto [\nu/B(t)]^{1/2}\,, \tag{6}$$

and the electron distribution maps to the synchrotron spectrum as

$$S(\nu,t) \propto B(t)\gamma(\nu)^{1/2} n[\gamma(\nu),t]\,. \tag{7}$$

Applying equation 7 to the solutions of equation 5, and assuming that the magnetic field doesn't fluctuate too much in space—taking $B(t)$ as uniform across the source—the synchrotron spectrum is also a broken power law, steepening at the critical frequency,

$$\nu_c(t) \propto \gamma_c(t)^2 B(t) \propto t^{-3/2}\,. \tag{8}$$

To be specific, I take $q(\gamma) \propto \gamma^{-2}$. The solution to equation 7 then has two parts. We would call a source "young" if it is observed when $\nu_c(t)$ is above our observing frequency (early times, flatter spectrum, low frequencies). For these sources, the synchrotron flux obeys

$$S_\nu \propto t^{3/4}\nu^{-1/2}\;;\quad \nu < \nu_c(t)\,. \tag{9}$$

Alternatively, a source observed when $\nu_c(t)$ is below our observing frequency would be "old" (later times, higher frequencies, steeper spectrum). For these sources, the synchrotron flux obeys

$$S_\nu \propto t^{-3/8}\nu^{-5/4}\;;\quad \nu > \nu_c(t)\,. \tag{10}$$

The high-ν spectrum is steeper here than in the standard solutions, because the B field decays with time.

Thus, a young source brightens with time (as more and more electrons fill the source). But an old source decays slowly with time (as synchrotron losses offset the ongoing input of new electrons). A source reaches its peak power when $\nu_c(t)$ equals one's observing frequency. This provides a useful definition of the synchrotron lifetime of the source: $\nu_c(t_c) = \nu$. Illustrative solutions are shown in Figure 13 and in Figure 14. The peak single-frequency power the source attains is

$$\max(P_\nu) \simeq \frac{0.5 P_{je}}{\ln(\gamma_m/\gamma_o)} \sim .05 P_{je}\,. \tag{11}$$

In the last I have relied on typical injection models which might have $\gamma_m \simeq (10^4 - 10^5)\gamma_o$. Although the local $B(t)$ field is important to the amplitude of P_ν away from its maximum, the peak $P_\nu = \nu_c S(\nu_c)$ depends only on P_{je}. Thus the peak radio power is a good measure of the electron power in the jet.

5.2. *Statistics: How the Population Evolves*

We do not, however, follow one source with time; rather, we sample a population containing a range of ages. Once $P_\nu(t)$ is known, this can easily be accounted for. If sources are created with zero power, the population obeys

$$\frac{\partial N(P_\nu)}{\partial t} + \frac{\partial}{\partial P_\nu}\left[N(P_\nu)\frac{dP_\nu}{dt}\right] = 0\,. \tag{12}$$

[2] It is important to remember that "equipartition" (and minimum pressure) are really measures of the synchrotron emissivity, which $\propto p_B p_e$, although they are often interpreted as measurements of the energy (or pressure) in electrons and field separately.

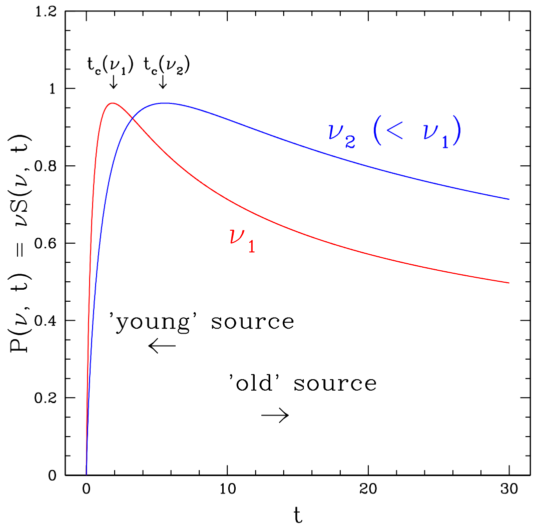

FIG. 13.— The time evolution of a radio source, seen at two different frequencies. At early times (when the source is "young"), the source brightens, as the jet supplies more electrons and field to the source. When the age of the source reaches the synchrotron lifetime, and becomes "old" the source begins to fade, as radiative losses overcome the ongoing supply of new electrons. Because the synchrotron life is a function of particle energy, and thus observing frequency, a source can be young at a low frequency and old at a high frequency.

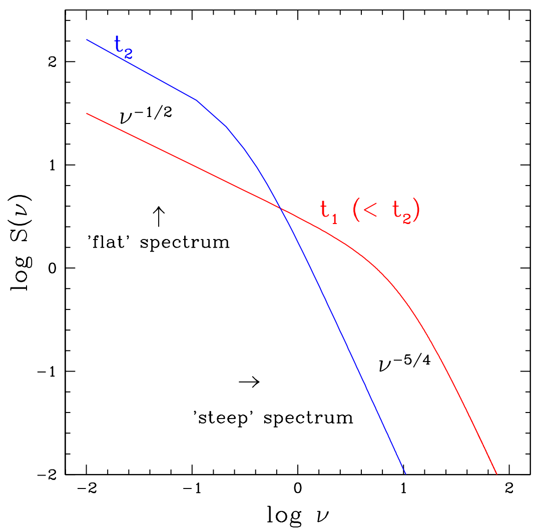

FIG. 14.— The spectrum of radio source, seen at two different times. At low frequencies the source appears "young", with a flatter spectrum; at high frequencies the source appears "old", with a steeper spectrum. Note the steeper high-frequency spectrum here, compared to standard spectral-aging models – due to the decay of the mean magnetic field with time as the source expands.

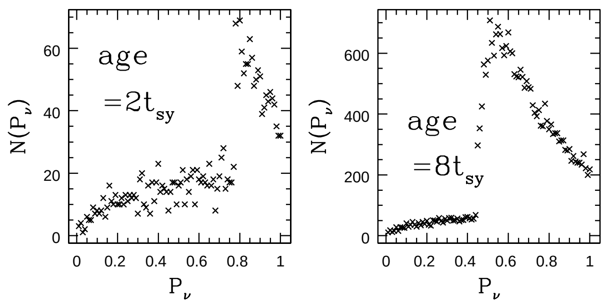

FIG. 15.— The time evolution of a population of cluster-center radio galaxies. In this simple model, sources are created at a steady rate, each starting life at zero radio power; all sources have the same intrinsic jet power and the same synchrotron lifetime. The observed variation is entirely due to evolution of individual sources. The horizontal axis is normalized to max P_ν, from equation 11.

In a steady system, this gives $N(P_\nu) \propto 1/(dP_\nu/dt)$. This has two branches, for young sources which brighten with time, and for older sources which grow fainter with time; a simple illustration of this is in Figure 15. Thus, if the toy model used here—steady creation of new sources and constant jet power in those already born—continues to operate, the population becomes dominated by older, steep-spectrum sources which decay only slowly with time. The steep-spectrum sources, being older, will be larger than the smaller (younger) flat-spectrum sources.

How does this toy model compare to the CCRS samples we have? Again looking ahead to §6, where I find synchrotron ages to be much less than the age of the cluster, we would expect almost all of the CCRS samples to contain large and steep spectrum sources. This is not the case; while many CCRS do match this description, many are still smaller and flat spectrum. Most of the CCRS population seem to be no more than a few t_c old. (I return in §7 to what this requires of the duty cycle of the central AGN). Referring to Figure 15, the mean or "typical" radio power of a CCRS will be somewhat less than the maximum possible:

$$\langle P_\nu \rangle \sim \left(\tfrac{1}{2} - \tfrac{2}{3}\right) \max(P_\nu) \sim O(10^{-2}) P_{je} \, . \tag{13}$$

That is, the mean P_ν of a sample of sources will be a few per cent of the electron power in the jet.

5.3. *Summary: Radio Power*

The most important point here is qualitative: a source will evolve in radio power even while its jet power stays constant. Young sources will grow brighter with time, and old sources will slowly fade. It follows that the radio power is an imperfect tracer of the jet power. For a particular source we must know much more than the current-epoch radio power if we want to learn about the jet.

We can, however, make statistical statements. From the known evolution of the P_ν/P_{je} with time, we can use the distribution of radio powers of a sample of sources to learn about P_{je}. I find that $P_{je} \ll L_{62.5}, L_{cc}$ for nearly all CCRS in the two samples in hand. Thus, the power in the electron component of the jet is insignificant compared to the X-ray cooling rate in nearly all cases.

However, the jet contains more than electrons. We know it transports magnetic energy, and it may contain other particle species as well. Can anything be said about the other components in these jets?

6. **Toy Models: Dynamics**

We can measure more than the single-frequency radio power of the source. With good radio images we can learn its morphology and its size. We can measure its radio spectrum; for the brightest sources the spectrum has been measured over several decades in frequency, which allows comparison to the predicted spectral steepening (as in Figure 14). The magnetic field cannot be measured directly, but decent indirect estimates can be obtained by combining radio and X-ray data (minimum pressure, ambient X-ray pressure, Faraday rotation). With this information in hand, we can use dynamical models to explore the total jet power.

6.1. *Radio Sources as Bubbles*

Once again, the place to start is with the simplest plausible model. For amorphous CCRS, this is indeed simple. We can describe the radio halo as a quasi-spherical bubble, fed by a jet whose power P_j stays constant in time. If the jet disrupts close to the galactic core, but continues to be powered by the AGN, it will deposit its mass and energy more or less isotropically into the surrounding plasma. This plasma will respond by expanding into the plasma of the cluster core; if the expansion is subsonic relative to the plasma—as is likely for these sources—the internal and external pressures will approximately balance. As long as the energy input P_j stays constant, the expansion rate of the bubble will be determined by the mean energy density within the bubble, and the pressure structure of the local cooling core. (More details are given in Owen & Eilek 1998 and Owen, Eilek, & Kassim 2000). Figure 7 shows a cartoon illustrating this. The radius of the bubble is governed by

$$4\pi R^2 p(R) \frac{dR}{dt} = \frac{\Gamma - 1}{\Gamma} P_j \qquad (14)$$

if the plasma in the bubble has an adiabatic index Γ. If the external pressure falls off as $p(R) \propto R^{-3/4}$ (typical of cooling cores), the bubble grows as

$$R(t) \propto \left(\frac{P_j t}{p_o} \right)^{4/9} , \qquad (15)$$

where p_o is the ICM pressure at some fiducial radius r_o.

The internal energy, E_i, in species i is determined by

$$\frac{dE_i}{dt} = P_{ji} - p_i \frac{dV}{dt} - \Lambda_i \qquad (16)$$

for species i, which can have radiative losses Λ_i, and which can be plasma (with $E_i = p_i V/(\Gamma_i - 1)$; I follow ions and electrons separately), or magnetic field (with $E_B \simeq p_B V$ for a tangled field). Once we have the $R(t)$ solution, from equation 15, we know $V(t)$ and equation 16 gives us the B field directly:

$$\frac{B^2(t)}{8\pi} \propto \frac{P_{jB}}{P_j} \left(P_j t \right)^{-1/6} . \qquad (17)$$

This shows that $B(t)$ *drops* with time, due to the density ramp into which the source expands, which causes $V(t)$ to grow faster than linearly with time.

It should be noted here that this model describes only the *mean* field, throughout the bubble; it does not describe the inhomogeneous magnetic structure (due to filaments, internal flows, and so on) which we know must exist. This model also does not consider the more complex physics which will become important later in the source's evolution. It seems likely that instabilities—Rayleigh-Taylor, Parker, magnetic tearing and reconnection—will eventually mix the radio plasma with the ambient ICM. In addition, once instabilities (or simply asymmetry in the local ICM) break the simple spherical symmetry, buoyancy will also affect the structure of the source. Comparing the radio and X-ray data, it looks as though some sources (e.g. 3C84 in Perseus, Fabian et al. 2002, or 3C317 in A2052, Blanton et al. 2003) have not yet mixed significantly with the local ICM, but that others (e.g. M87, Nulsen & Böhringer 1995; Young et al. 2002) are well mixed.

6.2. *Apply to Real Sources*

This simple model can be tested against two classic bubble sources, 3C317 (figure 8) and M87 (figure 11), and also for the unusual source 3C338 (figure 12), which is probably also a halo-type source, distorted by local "weather." For each of these we have good enough radio images to locate the outer edge of the source, and good X-ray information exists on the pressure distribution of the ICM in the cluster core. We also have (indirect) evidence on the amount of mixing of radio and cooling-core plasmas; based on the detection, or not, of X-ray "holes", we can speculate that the plasmas are well mixed in M87, but not in 3C317 or 3C338. Finally we have radio-derived minimum pressures and Faraday rotation information.

From these data we can use equation 15 to find the product $P_j t$; and compare the mean field from 17 to the field necessary for pressure balance with the ICM, to estimate P_{jB}/P_j. Scaling to 10^{44} erg/s, I find $P_{44} t_{Myr} \sim$ 100–700 for the three sources. It seems likely that the magnetic field provides a substantial part of the pressure support of the bubble; if this is the case, the ratio $P_{jB}/P_j \sim 1/10$–$1/2$ in all three sources.

6.3. *Radio Spectra and Source Ages*

How can we go further? In order to break the (P_j, t) degeneracy, we need independent information on the age. If we accept the traditional injection-plus-aging model of the radio spectrum, developed above, we can use the critical frequency (equation 8) to get new information. Collecting the results from the spectral and dynamic analysis, this model says

$$\nu_c(t) \propto \frac{P_j^{1/2}}{t^{3/2}} \left(\frac{P_j}{P_{jB}} \right)^{3/2} . \qquad (18)$$

This addition completes the set. We can use it together with the results above to determine P_j and the source age independently.

In M87, this analysis gives $P_j \sim 6 \times 10^{44}$ erg/s, which is a bit above the minimum-P_j estimate from Owen, Eilek, & Kassim (2000), and well above the cooling-core power in this (X-ray weak) cluster. For 3C317 and 3C338, this analysis finds jet powers an order of magnitude higher than for M87. These are stronger cooling cores than Virgo, and the factor ~ 10 higher ICM pressure is what leads to the higher P_j here. If this model is right, these sources also have jet powers well above the X-ray luminosity of their cooling cores.

6.4. *Summary: Dynamics*

The unusual, quasi-spherical core-halo structure of many CCRS can be easily modeled as a "bubble," driven by energy input from the jet, and expanding against the pressure of cooling core. From the size of such sources we can derive a robust estimate of the product $P_j t$. From knowledge of the magnetic field inside the bubble we can estimate the fraction of the jet power that is carried electrodynamically: $P_{jB}/P_j \sim 0.14$–0.5 seems to be the case.

To go further, and learn the jet power, we need a separate estimate of the source age. Using the traditional approach, spectral aging, I find that the three sources considered here must be quite young (a few Myr), in order to keep synchrotron losses from being too important. Combining this with the dynamical estimate of $P_j t$ requires powerful jets. Because this spectral aging model may not fully describe the physics of these sources—as I discuss below—the jet power derived this way is probably an upper limit, say a "maximal" jet power. Comparing to the results in §5, I find $P_j \gg P_{je}$; the electrons are only a small component of the jet power. This analysis also suggests that the total jet power can be significant compared to the X-ray power of the core.

7. **Toy Models: Critique**

These conclusions are attractive, but they are only as good as the theories in which they are based. Are these models good enough? Three caveats are in order regarding the toy models I have presented here.

7.1. *Not All Sources Are Simple Bubbles*

Not all CCRS can be described as homogeneous bubbles. One complication is that some sources (such as Hydra A and Cygnus A) clearly retain the identity of their jet. Others are complex; they appear tailed, but may also contain a large, faint halo. One example is the CCRS in A2029 (Figure 5); another is M87 itself (Figure 11), which might be called a tailed source if it were fainter and seen in a less deep image.

Tailed sources can be modeled, using the methods of §5, but necessarily with more complexity. From observations of similar, but brighter, sources in the general population, we know that the jet retains at least partial coherence while propagating through cluster gas. It distorts close to the core, forming a "tail", but the flow continues on into the tail. The length of the tail is determined mainly by its momentum flux (as the thrust from the directed flow pushes out against the ICM pressure), but buoyancy and flows in the ICM may also be important. In general the tail length grows less rapidly than the flow speed within the tail, so that plasma reaching the end of the tail must slow down, move aside, and be stored in a larger region (the "cocoon" of the tail flow). Growth of this cocoon will be governed by energy and mass conservation.

The qualitative results of these tailed-source models are similar to the bubble models above (although different in detail). The volume of the tail will grow faster than linearly with time, so that the mean magnetic field will decay with time. Thus the source will initially brighten in the radio, and later slowly fade, as do the simpler bubble models. This issue, while very interesting from the point of view of radio source physics, should not affect the general arguments here about CCRS jet power and evolution.

7.2. *Is Spectral Aging Right?*

A more serious problem with the simple models in this paper is their reliance on standard models of the relativistic electron evolution. The weakest links in the models of §5 and §6, in my opinion, are the assumptions that (i) relativistic electrons do not undergo *in situ* acceleration after they are "injected" by the jet, and (ii) that they radiate in a magnetic field which is uniform throughout the source. This set of assumptions predicts, as we saw in §5, rapid decay of the high-energy electrons and rapid steepening of the radio spectrum. Requiring the frequency at which the spectrum steepens to be as high as it's observed to be, in the three sources under consideration, forced those sources to be quite young. This in turn required very high jet powers, in order for the sources to grow to their present size against the high ambient pressure of the cooling core.

Detailed studies of other radio galaxies have pointed out that this standard, simple picture is not necessarily right. The high frequency steepening commonly observed may be due to quite different physics (Katz-Stone et al. 1993). What else can explain spectral steepening without requiring such a young source? One possibility is *in situ* particle acceleration (say by shocks or plasma turbulence) which keeps the electrons energized despite ongoing synchrotron losses. Another is the effect of magnetic fluctuations on the radio spectrum; even though the mean field may be uniform throughout the source, small-scale magnetic fluctuations can have a strong effect on the synchrotron spectrum (due to the $\gamma^2 B$ dependence of the emitted frequency, equation 6; c.f. Eilek & Arendt 1994 for specific models including broken power laws).

7.3. *What About Duty Cycles?*

It seems unlikely that the radio jet in a CCRS remains at constant power throughout the life of the cluster. Dynamical models of specific sources suggest they are only several tens of Myr old. Furthermore, not all of the CCRS have the steep radio spectrum which the simple models predict; this is consistent with existing sources being only a few times their synchrotron age. Both of these arguments point to the AGN switching into a low-power state after something like 10–100 Myr at high power. However, because nearly every bright galaxy in a cooling core hosts a currently active AGN, the low-power state cannot last for long. The low-power cycle must last long enough for the large "relic" radio source to fade,[3] but not as long as it spent in its high-power state. When it again becomes a high-power jet, the cycle would restart, and a new "young" radio source would begin to grow.

It must be emphasized that the above argument is very uncertain. We do not know how relic radio sources behave—in fact their relative scarcity in the universe is a major problem for the radio source models in general, including those presented here. And we have no idea what controls the duty cycle of the AGN itself. However, for the purposes of this paper we can note that the estimates of typical jet power in a sample of CCRS should probably reduced by some factor, not too large, compared to those derived in §4 and §5 (which were based on constant jet power).

8. Concluding Remarks

My focus in this paper has been the nature of the radio galaxies which sit in strong cooling cores, and their role in the energetics of the cooling core. To that end, I reviewed the data and also discussed the physics of radio source evolution. In order to know how important these radio sources are to the cluster core, we need to know the power carried by their jets. Because we cannot measure that power directly, we need to understand the physics of the radio sources in order to use the data to estimate the jet power. Two important conclusions emerge.

First, we have learned that central AGN with associated radio sources are common, perhaps universal, in strong cooling cores. Many of these central radio galaxies are interacting strongly with their surroundings, and must be energizing their surroundings to some extent. The central AGN seem to undergo high and low power periods, with a cycle time ~ 100 Myr, but with most of the duty cycle spent in the "high" phase. It is important to realize that the radio power we measure is not a good measure of the jet power, for any given source, because the radio power varies significantly over the lifetime of the source even if the jet power remains constant.

Second, we have seen that models of radio source evolution can be used to constrain, but not uniquely measure, the jet power, P_j. The mean radio power in the sample provides an estimate of that part of P_j carried by relativistic electrons, P_{je}. For nearly all of the CCRS this power is small compared to the X-ray power of the cooling core. This is probably a lower limit to the true jet power. It is interesting to note, however, that $100 P_{je} \gtrsim L_{62.5}$ for all of the RASS sample, and $100 P_{je} \gtrsim L_{cc}$ for 2/5 of the Peres sample. If particle acceleration in these AGN behaves similarly to cosmic ray acceleration in our galaxy, there could be substantially more energy in ions than electrons (up to the factor ~ 100 for galactic cosmic rays), making the jets energetically important to many cooling cores.

Turning to constraints on the total jet power (in electrons, ions and magnetic field), dynamical models of the sources give us an estimate of the product $P_j t$. If we also assume the observed radio spectral breaks are due to simple synchrotron aging, we gain an independent estimate of the source age, and thus of the jet power. When applied to three well-studied CCRS, this analysis suggests the total jet power can be quite large, $P_j \gtrsim L_{cc}$. Because the spectral aging argument is not strong, this estimate is probably an upper limit to the true jet power; but it does suggest that the jet contains more than just its electron component.

In summary, it seems likely that central radio galaxies play an important role in the energetics of at least the inner region of the cooling core. However, because current models cannot really pin down the jet power, the preceding statement can be only qualitative. In addition, because the density and temperature profiles are so uniform in all strong cooling cores, it seems unlikely that these short-lived, rapidly evolving central radio galaxies control all of the physics in these cores. But they are probably part of the answer to the questions posed in the introduction.

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[3] Just how that can happen quickly is not clear; one possibility is turbulent dissipation of magnetic field.

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