

# RADIO JETS IN COOLING CORES

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## Abstract

Almost every strong cooling core contains an active radio galaxy. Combined radio and X-ray images reveal the dramatic interaction which is taking place between the radio jet and the central cluster plasma. At least two important questions can in principle be answered by comparing the new data to theoretical models. The first is how the radio jet propagates, and disrupts, in the cooling core environment: why are these cluster-center radio sources unusual? The second is the effect the radio jet has on the cooling core: is it energetically important to the core? Thanks to the new data we are beginning to be able to answer these questions.

## 1 Introduction

One topic of this meeting is the interaction of jets with their environment. This is an ideal area for the combination of radio and X-ray observations. I will focus on one particular aspect: the interaction of cooling cores in galaxy clusters with radio jets that come from the massive black holes in the cluster center.

### 1.1 What is a cooling core?

We have known since the earliest days of X-ray astronomy that the atmosphere in some clusters of galaxies has an unusually dense, X-ray bright core. The high gas density means a short cooling time. If the thermal history of the gas is simple – if it is heated by the cosmological collapse of the cluster, but subject to nothing else since that collapse – the short cooling time means hydrostatic equilibrium cannot be maintained in the core. A slow, cooling-driven collapse will occur instead. This has been called a “cooling flow”. The simplest interpretation of the observations suggested that hundreds of solar masses per year are collapsing into the cores of these clusters, with large amounts of cool to very cool gas residing in the inner tens of kpc.

However, we now know things are not so simple. With the advent of the newest X-ray satellites, we now know that the large amounts of cool gas which the simple models predicted are not there. The dense cores of these clusters are indeed a bit cooler than the rest of the atmosphere (e.g., De Grandi & Molendi 2002). However, there is not nearly as much cold gas as the early models predicted (Peterson et al. 2004) and certainly no evidence for smooth inflow. In fact, *Chandra* images of these clusters show that the inner tens of kpc have a complex structure, not at all the spherically symmetric, near-hydrostatic atmosphere that the simple cooling flow models envisioned.

Thus, with little evidence for cooling and none for simple inflow, these dense cores need another name. I call them “cooling cores”.<sup>1</sup>

Cooling cores are infrequent among galaxy clusters. They occur in unusually concentrated, massive clusters which seem to form in regions of high galaxy density (Loken, Melott & Miller, 1999; Bullock et al. 2001). The high gas density in the cores seems to be a consequence of this high concentration, which compresses large amounts of intracluster gas into quite small cores; the size of the gas core is typically  $\sim 100$ – $150$  kpc. The short cooling time follows directly from this, and thus is due in the end to the happenstance of the cluster’s formation.

### 1.2 What is a cooling-core radio source?

A massive, bright galaxy sits at the center of every cooling-core cluster. Nearly all of these central galaxies contain an active galactic nucleus (AGN) which currently supports a cluster-center radio source (CCRS) (initially pointed out by Burns, 1990; revisited

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<sup>1</sup>The name “cool core” might be even better; but in order to retain the connection to the older “cooling flow”, which is still in common use, I choose “cooling core”

by Marković 2004, also Eilek 2004a,b, “E04”). While it has been suggested that this is due to the cooling flow, it seems more likely due to the massive galaxy itself. Ledlow & Owen (1996) show that the probability of a galaxy having a radio source increases with galaxy size, so that galaxies as big as these are very likely to have a radio source.

These CCRS are particularly interesting. When we look at large samples of CCRS, it becomes clear that they are not typical of the general radio source population. It must be that the unusual conditions in the cooling core affect the CCRS in dramatic ways. The CCRS in turn has a strong effect on the gas in the cooling core, disturbing its simple equilibrium and possibly providing significant heating to the gas.

In this paper I explore both sides of this interaction. I present an overview of the data, and some theoretical work which may address some of the important physics. The keen reader can find more detail in Eilek et al. 2003, E04 and papers cited therein.

## 2 The data reveal the interactions

The place to start is with the data. Samples with many objects provide insight that observations of one or two sources cannot. I have formed two complete samples of nearby cooling-core clusters, one flux limited, one volume limited (details in E04). These contain a total of 41 cooling-core clusters with good information on the CCRS’s. My sense of the nature of CCRS’s has come from these samples. Another sample is that of Eilek & Marković (2004; “EM04”), which contains equal numbers (12 each) of rich clusters with and without cooling cores. My insight into the nature of cooling cores comes mostly from this sample. Finally, I have benefited from easy access to the data in two larger samples: the Owen-Ledlow sample of 250 radio galaxies in Abell clusters (e.g., Owen & Ledlow 1997), and the Ledlow et al. (2004) work on X-ray properties of 288 Abell clusters.

### 2.1 The radio source disturbs the cooling core

We know the CCRS disturbs the cooling core. This is apparent in essentially every *Chandra* image of a cooling core. At this writing, 10 of the 12 cooling cores in the EM04 sample have public-access *Chandra* data. All of these show disturbances in the inner 20-40 kpc of the cooling core, which is also the scale of the CCRS. Some of the disturbed cooling cores are quite dramatic,

with apparently spherical “bubbles” and “ghost cavities”. Others are more subtle, with asymmetric inner cooling cores, in which the radio source appears to have displaced the intracluster medium (ICM), or with complex interactions and apparent mixing between the radio source and ICM. In addition, faint, ring-like features have been seen on larger scales in the X-ray gas of two clusters (Perseus, Fabian et al. 2003; and Virgo, Forman et al. 2004). These features appear to be either sound waves or shocks, centered on and driven by the AGN.

### 2.2 The cooling core disturbs the radio source

We also know the cooling core disturbs the CCRS. Nearly all (36 of 41) cooling cores in the E04 sample contain detected radio sources; I suspect more will be detected with deeper observations. Of these, 16 are large and bright enough to be well imaged. Very few of these are “normal” radio galaxies. To explain this I need briefly to explain what a normal radio galaxy is.

Almost all radio galaxies are jet-driven. Their morphology is determined by the interaction of the jet with its surroundings. In nearly every case the directed jet continues from the galactic core all the way to the extremities of the radio source, tens or hundreds of kpc out. The jet flow may continue directly to an outer hot spot, as in classical double radio galaxies, or it may undergo a sudden transition but continue on as a broad tail, as in tailed radio galaxies (e.g., Eilek et al. 2003).

By comparison, only two of the E04 CCRS sample are “normal” radio galaxies. These are Cyg A and Hyd A, two of the most powerful sources in the nearby radio sky. The rest of the well-imaged CCRS in this set are diffuse, amorphous sources. They have a radio-loud core, which tells us the AGN is currently active, but collimated jets exist only on kpc or sub-kpc scales. It seems that the jet is disrupted close to the galactic core, but its energy flow continues in a less collimated manner into the ambient cluster gas, creating a diffuse, amorphous halo.

### 2.3 Three examples

I illustrate with three examples, each showing a different type of interaction between the radio source and the cooling core. I show the radio and X-ray images separately, to show both structures clearly. Each source illustrated has a similar spatial scale, extending  $\sim$  30-40 kpc from the core.

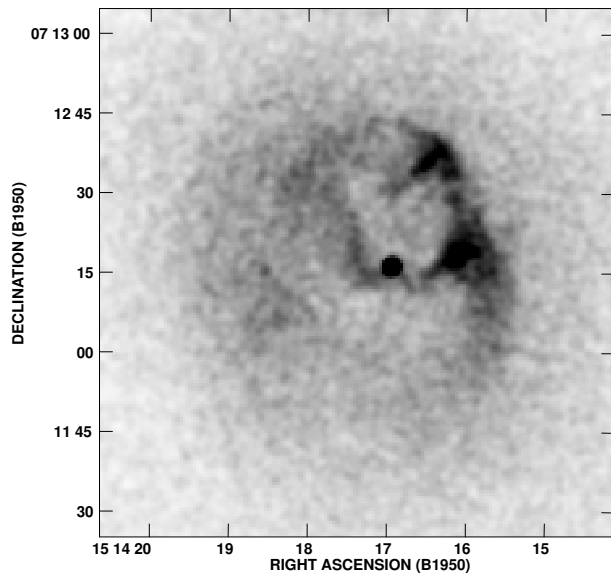


Figure 1: X-ray image of the cooling core A2052, linear extent  $\sim 60$  kpc. The bright core, which hosts the AGN, is apparent in the center of the figure, as are the “bubbles” which seem to have been evacuated by the radio source. Archival *Chandra* image, smoothed to  $3.0''$ . See also Blanton et al. (2003) for detailed analysis.

**3C317 in A2052** is a striking example of cavities in the X-ray loud gas (apparent in Fig. 1) which have been created by the radio source (shown in Fig. 2). The clear cavities tell us that the X-ray and radio plasmas are separated rather than well mixed. The brighter north-south regions of the radio halo coincide with the X-ray cavities, but the radio halo also extends beyond the cavity edges, into the less disturbed regions of the cooling core. This radio source has a strong radio core and a pc-scale jet. No jet has been detected on Very Large Array (VLA) scales (kpc or greater), but the bright radio “tail” to the south is suggestive of a semi-collimated flow from the core into the radio halo.

**3C338 in A2199** is an unusual source in both radio and X-rays. Figure 3 and 4 show that the radio source and inner X-ray plasma seem to avoid each other. The X-ray gas shows an enhanced region to the north of the AGN, while the radio source is offset to the south of the core. The radio source again has active, two-sided pc-scale jets, which continue to kpc scales and then grow very faint. The region between the core and the bright radio filament to the south is filled (at least in projection) with enhanced X-ray emission.

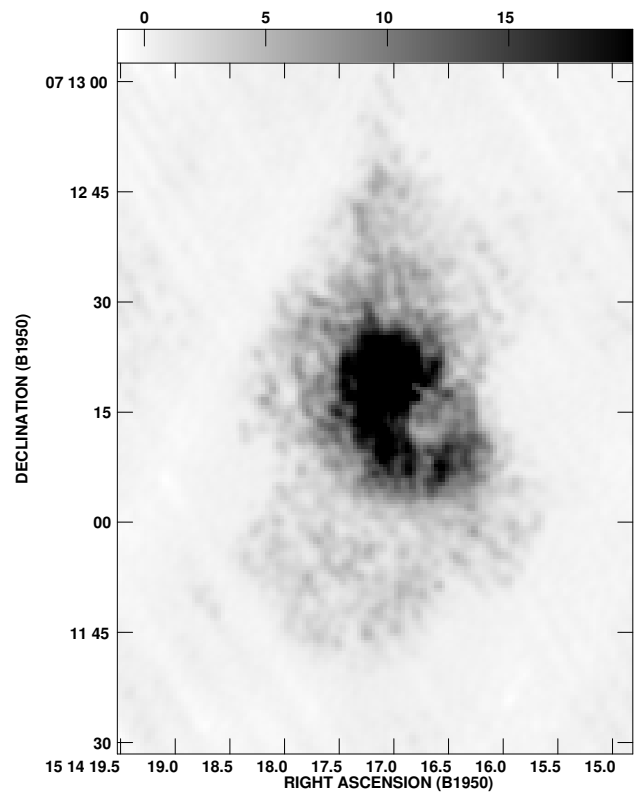


Figure 2: The radio source 3C317 in the core of A2052. The AGN, which shows a pc-scale radio jet, is in the center of this image but burnt-out in this exposure. The scale of the image is similar to Fig. 1. The radio source appears to fill the cavities apparent in Fig. 1 but also extends further to the north and south. VLA image from Owen & Ledlow (1997); see also Zhou et al. (1997) for more detailed study.

**M87 in the Virgo cluster** is an example of a more complex interaction between the radio and X-ray plasmas. Figure 5 shows that the X-rays display a bright core, centered on the galactic nucleus, and also two bright extended “tails” which lie to the west and southeast. The radio image shows a very bright inner core (which contains the famous jet, to which I return in Sect. 4), and bright “tails” to the west and southeast, all within a larger, amorphous halo. Both the radio and X-ray “tails” are suggestive of flows within the halo; however they do not coincide in detail. We also know from radio work this halo has a well-defined edge, which implies that the halo has expanded (rather than diffused) into the X-ray core. The lack of X-ray holes, however, tells us that there has been good mixing of the radio and X-ray plasmas across the edges of the radio halo.

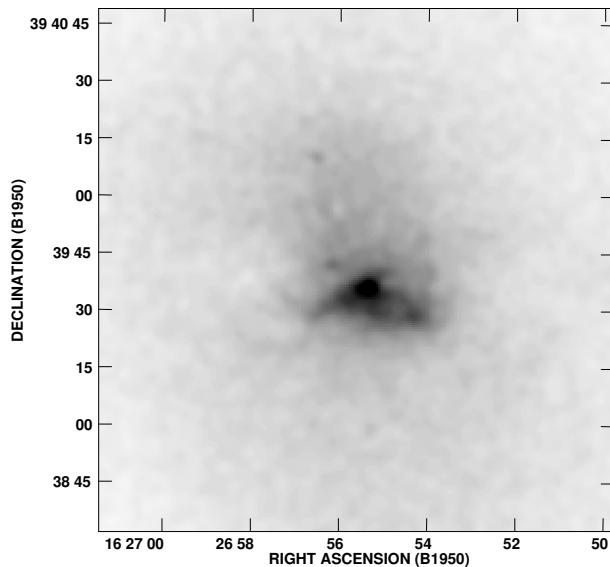


Figure 3: X-ray image of the cooling core in A2199, with linear extent  $\sim 75$  kpc north-south. The AGN coincides with the X-ray bright spot in the center of the image. The inner X-ray core is quite asymmetric about this core, with an elongation to the north, a bright layer just to the south, and faint “cavities” to the east and west of the core. Archival *Chandra* image, smoothed to  $1.5''$ . See also Owen & Eilek (1998), Johnstone et al. (2004).

## 2.4 Is this the whole story?

Can we generalize from these examples to all CCRS? Two points come to mind.

First, it has been suggested that these core-halo sources are the projection of a normal, jetted radio galaxy seen end-on. However, the frequency of such sources in the CCRS population, and the fact that the 4 (out of more than 150 well-imaged) Owen-Ledlow sources which are amorphous *are in cooling cores*, argues against this being just a projection effect. It is also worth noting that many of the CCRS which appear to have normal tails in published images, turn out in deeper images to have a diffuse halo (examples are A2597, Clarke 2005, or A2029, Marković 2004).

Second, the rest of the CCRS sample (20/36) are small, faint objects. Some are unresolved by Owen & Ledlow (1997); some are resolved but are too small and faint to be well imaged; and images of some are only available in the low-resolution NRAO VLA Sky Survey (Condon et al. 1988). These could be young sources, which have not yet grown large and bright, or they could be

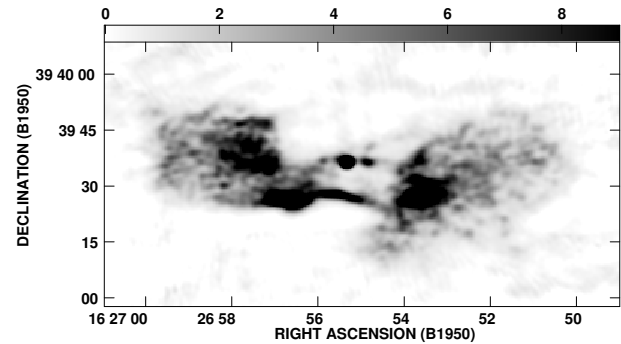


Figure 4: The radio source 3C338 in the core of A2199. This north-south extent of this image is about half that of Fig. 3; no radio emission has been detected on larger scales. The AGN, which coincides with the bright spot at the center of the image, contains a two-sided, pc-scale jet which connects to the small kpc-scale jets visible to the east and west of the core. The radio-bright filament to the south, which appears jet-like, does not coincide with any feature in the galaxy. VLA image from Owen & Ledlow (1997); see also Owen & Eilek (1998).

due to jets which are intrinsically weak. We don’t know which is the case; but looking ahead to my speculations in Sect. 4, it’s tempting to identify these as young, restarted jets, and suggest that their larger-scale structure from previous activity cycles has faded.

## 3 How does the radio jet affect the cooling core?

Disturbances of the cooling core by the CCRS are common. We know why the disruption occurs: mass and energy from the radio jet are slamming into the gas of the cooling core. What we don’t understand is the energetics of the system. What is the jet power? How important is this to the energetics of the gas in the cooling core? Because we can’t measure the jet power directly, we must turn to models. In this section I describe two types of models, which together can constrain the jet power.

### 3.1 The general population: dynamics?

One approach uses simple dynamical models to relate the size of the source to the jet power and the source age. This can be applied to sources with good enough radio and X-ray data to understand the morphology of the radio source and the structure of the local X-ray gas.

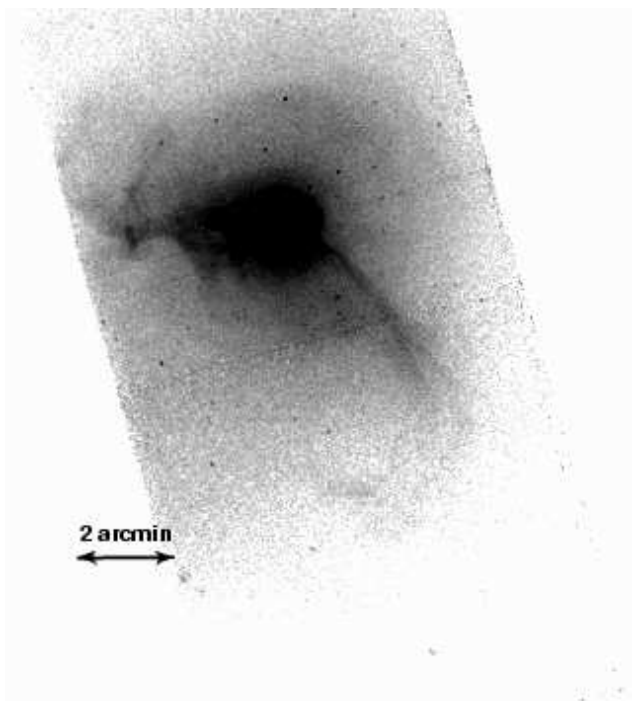


Figure 5: X-ray image of the core of the Virgo cluster. The north-south extent of the image  $\sim 80$  kpc. The AGN again sits in the central X-ray peak; striking features include the “tails” to the east and the southwest, and the ring-like structures centered on the core. Complex smaller-scale structure exists in the inner core, which is burnt out in this image. See Forman et al. (2004), also Kraft et al. (2005), for more details. *Chandra* image from Forman et al. (2004).

This method should be thought of as a toy model, because we do not really know the three-dimensional structure of a given source (although we know CCRS as a class are not just “normal” radio sources seen in projection). The radio haloes and X-ray cavities must be inflated against the pressure of the ambient gas. The simplest model involves ongoing energy input to a quasi-spherical “bubble” which expands due to its own internal energy (e.g., Fabian et al. 2002, E04). At late times buoyancy will also contribute to, or even dominate, the growth of the source (Churazov et al. 2001). Similar models can be developed for tailed sources; but since only a few CCRS are clearly tailed these models have not yet been worked out in as much detail (E04)

The key result is that these models are degenerate in jet power and source age. The size of a driven bubble measures the total energy input over the life of the source,  $\int P_j dt$ . If we want to learn the jet power from this method we need a separate estimate of the source age. There are at least two approaches here, depending

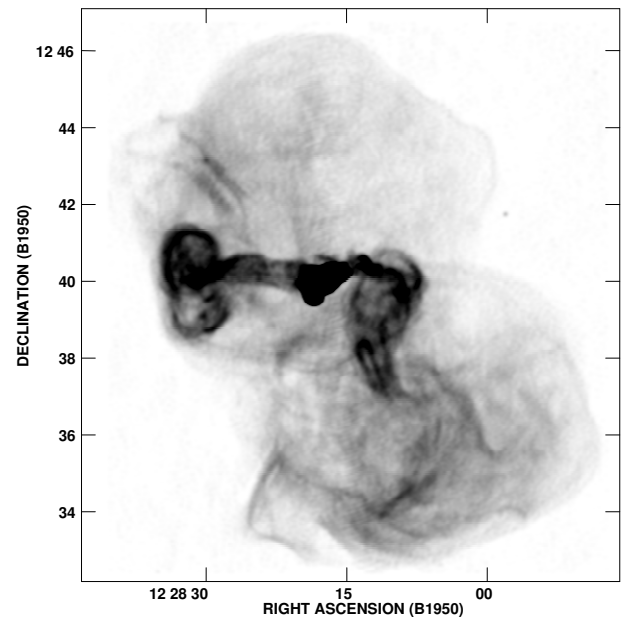


Figure 6: The M87 radio halo, in the core of the Virgo cluster. The north-south extent of the image  $\sim 80$  kpc, similar to Fig. 5. The AGN and well-known kpc-scale radio jet are within the burnt out region in the center of the image (but shown in Fig. 7). The “tails” to the east and the south, which appear to be flows in the radio-loud plasma, coincide approximately with the X-ray tails seen in Fig. 5. VLA image from Owen, Eilek & Kassim (2000).

on one’s taste.

One approach, traditional in radio astronomy, uses the observed radio spectrum and simple synchrotron physics to estimate the age of the source. This leads to quite short estimates for the source age, 1–10 Myr for our 3 example sources. However, any *in situ* acceleration of the electrons can offset radiative losses and make the source appear “younger” than it is. Thus, this approach only tells gives us a lower limit to the true source age, and a “maximal” jet power.

A more attractive approach comes from simple dynamics (e.g., Fabian et al. 2002), and applies to sources for which we have temperature information for the edges of the X-ray cavities. If these shells are cooler than the local ICM, we know they are not shocks, and the expansion speed of the bubble or cavity must be subsonic. This translates to a lower limit on the source age, and an upper limit on the jet power. When applied to our three example sources, this method suggests ages no shorter than 10–30 Myr, and jet powers no larger than

$4\text{--}70 \times 10^{44} \text{ erg s}^{-1}$ . For comparison, the X-ray powers of the cooling cores in these three objects are no larger than  $\sim 0.3\text{--}1 \times 10^{44} \text{ erg s}^{-1}$  (using the maximal cooling cores from Peres et al. 1998). Thus, it seems very likely that the jet power is significant to the energetics of these cooling cores – a conclusion which isn’t surprising given the strong disturbance of the cooling-core gas apparent in Fig. 1, 3 and 5.

### 3.2 The general population: radio power

Dynamical models require good radio and X-ray images of a given cluster core, which are not always available. At least half of the CCRS sample are too small or too faint to have good radio images. We can only measure the total radio power,  $P_\nu$ , for these sources. We know from synchrotron theory that  $P_\nu$  is a highly imperfect tracer of the underlying plasma energetics; so we must turn to statistics. If a CCRS evolves according to the simple dynamical models described above, we can use standard synchrotron analysis to predict how its radio power evolves with time. These models show that the radio power depends only on the fraction of the jet power carried in electrons. We can thus predict the mean ratio of radio power to jet electron power, over a sample of CCRS. Applying this to the E04 set of cooling cores, I find that this ratio is small. The core X-ray power exceeds the jet’s electron power by a large factor; the electrons are not energetically important by themselves.

What this method lacks is any way to estimate the total jet power. We must remember that the jet power can be carried by plasma and also by magnetic field, and that the plasma can be a mix of relativistic leptons, relativistic ions and cooler, thermal gas. It is interesting to remember that in our galaxy the energy in the relativistic ion component of cosmic rays exceeds that in electrons by a factor  $\sim 100$ . If this is also true for radio jets, then many jets in the CCRS sample will have total power comparable to the X-ray power of the cooling core in which they sit.

## 4 How does the cooling core affect the radio jet?

We know that radio jets in cooling cores have a good chance of being disturbed close to their origin. What we don’t know is why this happens. Indeed, we hardly know why jets in “normal” radio galaxies stay stable and propagate as they do. It may be that CCRS can be

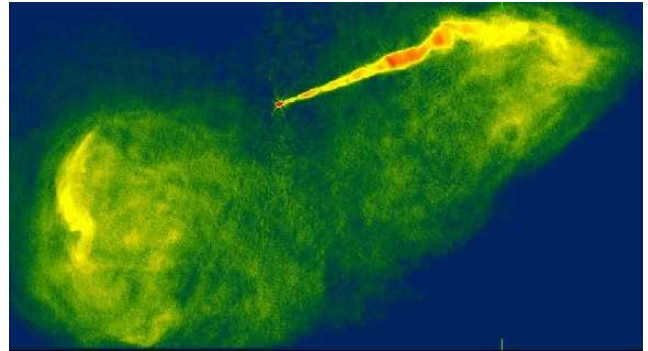


Figure 7: The inner radio core of M87, which appears as the burnt-out region in Fig. 6. This VLA image from Hines, Owen & Eilek (1989) shows the jet beginning to twist and disrupt at a projected distance  $\sim 3$  kpc from the core. Estimates of the jet angle to the line of sight range from  $\sim 20^\circ$  to  $\sim 40^\circ$ , based on proper motions within the jet and kinematics of the nuclear gas disk (e.g., Biretta et al. 1999, Ford et al. 1994).

a useful example for understanding the larger questions of jet stability and AGN duty cycles. In this section I’ll indulge in some speculations on the physics of these unusual sources.

### 4.1 Hints from the data

Over half of the well-imaged CCRS are not jet-driven on large scales. They do show a radio-loud core and pc-scale jets, which tells us the AGN in these sources is currently active. However, unlike most radio galaxies, the well-collimated jet does not continue past kpc scales in these objects (this is illustrated by the 3 examples in Sect. 2.3). This suggests that features which appear to be tails are, in reality, more like the broad flows within the M87 halo (as in Fig. 6). It follows that that, although the jet disrupts dramatically within a kpc or so of the AGN, the energy and mass flows continue into the CCRS. The radio jet and inner halo of M87 (shown in Fig. 7) may be an example of this. The jet is initially very well collimated, but after a few kpc it begins to bend and disrupt.

The environment in which a CCRS jet propagates is also unusual. Most radio galaxies arise from normal bright ellipticals. In these galaxies the gas core extends only  $\sim 1$  kpc (e.g., Brighenti & Mathews 1997), beyond which the jet propagates into a low density, low pressure region. In cooling cores, however, the jet must fight its way out through a much larger core. The dense, high-pressure region in cooling cores extends

out to  $\sim 50\text{--}100$  kpc (e.g., EM04). These unusual conditions may make the jet more susceptible to disruptive instabilities.

## 4.2 Hints from simple models

CCRS statistics tell us that nearly all cooling cores – and probably all if we look hard enough – contain an AGN which is currently “on”. But the simple models, described in Sect. 3.1, suggest that these sources are unlikely to be older than  $\sim 100$  Myr. These two statements can be reconciled only if the jet power fluctuates on a similar timescale. We might imagine, for instance, that the jet maintains a steady power for the time needed to develop a large radio halo, such as M87 or 3C317; then goes into a low-power stage, during which the radio halo fades or disperses; then goes into another high-power stage. Two things follow from this.

(1) The small, faint cluster-core radio sources are probably young and recently restarted. Their haloes from previous cycles must have faded. While such restarting has been suggested occasionally for an individual radio source, this is the first strong evidence of which I’m aware that such restarting may be common.

(2) The large-scale cluster-core radio haloes must disappear quickly. This is a long-standing problem for the general radio galaxy population, where long synchrotron lifetimes for the extended emission should keep a radio galaxy visible long after its jet has turned off. More rapid fading might be possible in these dense cluster cores, for two reasons. The higher core pressure makes higher magnetic fields likely, thus causing more rapid synchrotron aging for the relativistic electrons. In addition, the small turbulent scales likely in these cores could result in more rapid turbulent dissipation of the magnetic field. Both effects would conspire to kill the extended radio emission fairly quickly once the driving jet turns off.

## 4.3 Hints from theoretical modeling

There are some results in the literature which give us clues on the jet disruption and its ability to heat the cooling core.

First, analysis of a jet’s Kelvin Helmholtz stability such as those of Hardee (e.g., 2000, 2003, and references therein) provide insight. This work suggests that jet disruption happens when the instability develops to the point of allowing significant mass entrainment from the surroundings. Hardee also notes that jets which

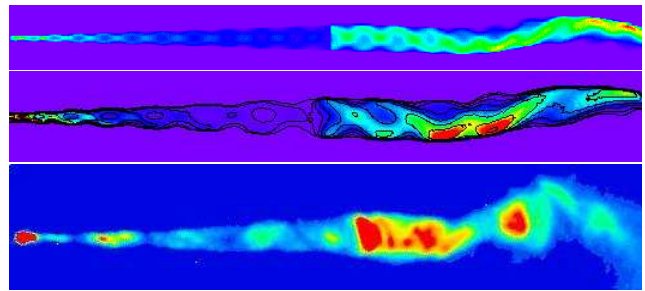


Figure 8: Comparing semi-analytic instability analysis of the M87 jet to the real thing. Top: a pseudo-synchrotron model of the jet, seen in the plane of the sky. The model assumes that helical and elliptical surface Kelvin-Helmholtz modes are excited, and that the pressure and wavelength of the modes jump midway down the jet. Center: the same model jet, seen at a viewing angle of  $40^\circ$ . Both from Hardee, Eilek & Lobanov, work in progress. Bottom: 15 GHz VLA image of the jet, from Owen, Hardee & Cornwell (1989).

generate a lower density lobe or sheath surrounding the jet flow should be expected to remain fairly stable. It may be that the extended high-density region of a cooling core prevents the formation of this stabilizing outer layer (Hardee, private communication).

Second, numerical simulations suggest that jets propagating into steep density ramps tend to destabilize. Rizza et al. (2000) demonstrated this with simulations of a jet propagating into a classical cooling flow atmosphere (see also Loken et al. 1993). We might expect such disordered jet flow to be effective at heating the ambient gas in the cooling core, and simulations are beginning to address this question. Omma et al. (2004) follow the development of a high-momentum, jetted radio source through a cooling core, with particular attention to its effect on the dynamical and thermal state of the cluster gas (see also Basson & Alexander 2003). Hughes, Hardee & Eilek (work in progress) are undertaking simulations of a perturbed jet propagating into a pressure ramp with an inner core, in order to study the effect of the jet on the cluster core as well as its stability.

Finally, it may be that we’ve caught one nearby jet in the act of disrupting. Lobanov, Hardee & Eilek (2003) used high-quality radio and optical images of the M87 jet to identify double-helical features in the inner jet which which are consistent with those caused by a Kelvin-Helmholtz instability. The dramatic twists and bends in the outer jet, apparent in Fig. 7, may be the development of the nonlinear stage of this instability.

Hardee, Eilek & Lobanov (work in progress; Fig. 8) are extending this analysis to determine whether physical conditions in the jet can be consistent with instability development as well as other dynamic and observational constraints known for this jet.

## 5 Concluding comments

X-ray and radio data are converging to make this an exciting time to be studying both cooling cores and the radio galaxies which sit at their centers. The new data raise at least as many questions as they answer, so we still have challenges ahead.

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