# The Outer Radio Halo: Typical of Atypical Radio Sources?

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**Abstract.** The outer radio halo of M87 is one of an unusual class of radio halo sources attached to cluster-center galaxies in cooling cores. The M87 halo appears to be a young source, partially mixed with the ambient thermal plasma, expanding rather like a bubble into that plasma. The radio jet provides a significant energy source to the thermal core plasma. In turn, flows in the X-ray emitting plasma appear to disrupt the radio jet and account for formation of the radio halo.

## 1 Cluster-Center Radio Sources

Nearly all large-scale radio galaxies fall into one of two morphological types. Type II sources are rare but bright. They contain highly collimated, probably supersonic jets which impact the ambient medium through a set of shocks, leaving the hot jet plasma behind in a visible radio lobe. Type I sources are more common but generally fainter. They also begin with collimated jets, which often spread or decollimate close to the parent galaxy. The jetted plasma continues to propagate into the ambient medium, perhaps subsonically, perhaps bouyantly. These two types separate well in radio power and parent galaxy magnitude: sources with $P_{1.4\mathrm{GHz}} \gtrsim C L_{\mathrm{gal}}^{1.65}$ ($C$ is a numerical constant) are Type II, while others are Type I (Owen 1991, Ledlow & Owen 1996).

Despite their different appearances, both Type I and Type II sources are similar in their underlying dynamics. Their linear size is determined, for a given external density and pressure, by the momentum flux in the beam (perhaps modulated by buoyancy and intergalactic winds in the case of Type I sources). Their volume is determined by the energy flux in the flow.

Where does M87 fit into this scheme? I believe it is neither a Type I nor a Type II. I think it is typical of amorphous radio galaxies which result from the unusual conditions at the centers of clusters with strong cooling cores.

Recently, Owen & Ledlow (1997) have compiled an excellent data base of radio galaxies in clusters. Nearly all of these sources fall in the Type I region of the (radio power, optical magnitude) plane. Approximately 150 of their sources have radio images which are good enough to reveal morphological information. Nearly all of these sources appear to be described by the basic dynamical model described above; but a few are different. Five out of the 150 are diffuse, closer to circular than linear (in projection), and generally amorphous in appearance. They all extend to tens of kpc from their cores.

When spectral information is available, these sources have unusually steep radio spectra. None of them shows evidence of a linear, collimated flow farther a few kpc from the core.

It is tempting to view these sources as truly amorphous – bubbles rather than jet-driven flows. As they are all associated with bright, cluster-center galaxies, they are unlikely to be normal Type I sources seen in projection.[1] In Owen & Eilek (1997) we argued from combined radio and X-ray data that another member of this set, 3C338 in A2199, shows evidence for a strong interaction between the radio jet and the local X-ray plasma. It appears that the radio jet has been disrupted by local conditions in the X-ray gas. Such an early disruption of the radio jet is likely to lead to an amorphous radio source, which expands like a "bubble", driven by its internal energy rather than by the momentum flux in its jet.

The outer radio halo of M87 (Klein 1997, Owen 1997) fits well into this set of amorphous, cluster-center radio sources. It is very similar in linear size, radio power, radio spectrum and location in a cooling core. In this paper I consider the M87 radio halo in this light.

## 2 The Radio Halo of M87

### 2.1 What are the Conditions in the Halo?

The outer radio halo of M87 is probably in pressure balance with its surroundings. The pressure in the ambient gas is $p_x \sim 2 - 4 \times 10^{-11}$dyn/cm$^2$ (Nulsen & Bohringer 1995). The low-resolution equipartition pressure in the radio lobe is $p_{eq} \sim 1 - 2 \times 10^{-12}$dyn/cm$^2$ (Feigelson *et al* 1987). However, this very likely underestimates the true pressure of the radio plasma, due to inhomogeneity, deviations from equipartion, and the possibility of mixing of thermal plasma. Thus, the radio lobes are probably in overall pressure balance with the ambient plasma.

The radio halo is inhomogeneous. Filaments are apparent in new images from Owen. The halo contains large-scale filaments emanating from the core, and smaller ones throughout the lobe (or possibly on its surface). Such filaments are regions of high magnetic field, high pressure, or both.

The radio halo is magnetized. The low-resolution equipartion field is $B_{eq} \sim 4 - 8\mu$G (Feigelson *et al* 1987). As with the pressure, this is probably an underestimate of the field. The field which would balance the ambient pressure is $B_p \sim 25 - 30\mu$G. Faraday rotation data find $B_{RM} \sim 20 - 50\mu$G in the inner few kpc, and suggest that the field is inhomogeneous, probably clumped in high-field flux ropes, and maintained by turbulence (Eilek 1997).

[1] All 5 amorphous sources belong to a "cluster-center" subsample of the Owen-Ledlow sources, defined as those identified with a bright galaxy, and located within 100 kpc of the X-ray peak as identified from ROSAT by Ledlow (1997, in preparation). In addition, the 4 of them with cooling-flow information (Peres & Fabian 1997) have strong cooling cores.

### 2.2 What's Happening in the Halo?

The new observations give insight into the physical state of the radio halo.

First, how well has the radio-loud plasma in the halo mixed with the ambient X-ray-loud gas? Older models of these amorphous sources discussed microscopic diffusion of relativistic particles through the ambient medium. Others suggested that macroscopic instabilities could lead to full mixing of the radio plasma with the X-ray gas. Both of these seem unlikely in the case of M87. The radio source has a well defined, sharp outer edge, which is apparent at all frequencies. Polarizaton in the south lobe (Rottmann *et al.* 1996) shows that magnetic field is parallel to edge of source. Both of these facts suggest a well-defined boundary, separating the radio plasma from the ambient X-ray plasma. As plasma cannot easily cross magnetic surfaces, this suggests the radio plasma and X-ray ambient gas remain separated.

However, the situation may not be quite so simple. There is no sign of a "hole" in X-rays (as has been detected around Cyg A by Carilli, Perley & Harris 1994). Thus it may be hard to invoke a fully isolated radio-loud bubble, despite the arguments above. The answer may lie in the fact that mass-loading across a well-defined MHD surface is possible through local, small-scale reconnection events. This is occuring, for instance, at the earth's magnetopause (*e.g.*, Lui 1985), indicating that some fraction of the incoming mass flux in the solar wind is admitted to the earth's magnetosphere. It may be that similar processes are occurring at the boundary of the M87 radio halo, admitting some slow mixing of thermal plasma with the relativistic, radio-loud plasma.

A second question is, how does the kpc-scale jet connect to the outer lobes? The new radio images clearly show filaments leading from the inner lobes into and throughout the outer lobes. I find this strong evidence that the outer lobes are still "alive", that is still being supplied with mass and energy, rather than being a relic of previous active epochs.

A third question is, how does the entire system connect to the dynamics of the X-ray gas? In addition, the X-ray isophotes show complex structure in this region. On large scales, $\gtrsim 50$ kpc, they are symmetrical and slightly elliptical (*e.g.,* Nulsen & Bohringer 1995), agreeing with approximate PA of stellar galaxy. However, the isophotes rotate and become strongly elongated in the inner region. Residuals from a spherical fit show a ridge-like X-ray excess which approximately coincides with the bright radio filaments (Feigelson *et al* 1987, Bohringer *et al* 1995). New ROSAT HRI data (Harris 1997) reveal this excess has the appearance of a bent sheet, or bow shock, centered on the core of the galaxy. Harris notes that the X-ray ridge appears to pass directly through the knot A-C complex in the jet. Thus, it seems clear that the thermal cluster gas has disrupted the jet of M87. This disruption may well be what has turned this galaxy into an amorphous radio source.

### 2.3 How old is the Radio Halo?

If the outer radio halo is still "alive", then we can apply the simple model of an energy-driven bubble, expanding at constant pressure. This has $V(t) \simeq (P_b/p_x)t$ (Eilek & Shore 1989), if $P_b$ is energy input to the lobe, and $V(t)$ is the volume of the lobe, and $p_x$ is the ambient pressure in the X-ray gas. Clearly this is a naive picture, ignoring gradients in $p_x$, mass loading from the ambient gas, and projection effects; however, these caveats should amount only to a factor of a few. Various estimates for the jet power in M87 agree on the range $P_b \sim 10^{43} - 10^{44}$ erg/s (Bicknell 1997, Reynolds 1997). Taking $P_b = 10^{43}$ erg/s gives an age $\sim 170$ Myr for the halo; taking the higher power gives an age $\sim 80$ Myr. The radio halo is still quite young.

What can the radio spectrum tell us? The lobe shows a range of steep spectral indices (Rottmann & Klein 1997), which are usually interpreted as evidence for particle aging. The situation is more complicated, however. The synchrotron age of electrons radiating at 1 GHz is 220 Myr in a $4\mu$G field, but only 10 Myr in a $20\mu$G field. This last is much shorter than the dynamical age of the source. Thus, either the particles spend much of their time in high field regions and undergo local re-accleration in the lobe, or they spend most of their time in low-field (interfilament) regions and radiation rapidly when they hit the filaments (Eilek, Melrose & Walker 1996). In either case, these short lifetimes also argue against the radio halo being a relic source.

## 3 The Energy Budget of the Virgo Core

The core of the Virgo cluster is an active place. It is anything but a slow, spherically symmetric cooling inflow. The radio data tell us that outflows exist, on a scale $\sim 20 - 40$ kpc, driven by the central galaxy. The X-ray data show us direct evidence of a non-static atmosphere, and (if the X-ray sheet is a bow shock) strongly hint at transonic motion of M87 relative to the cluster. The radio also tells us that dynamically significant magnetic fields exist in the very inner core, and probably throughout the entire core region. These fields are very likely to be maintained by transonic turbulence (of which we see a trace in the velocities of the emission line clouds in the inner core; Sparks, Ford & Kinney 1993)

The total energy thermal energy in the core is $U_{th} \sim 1 \times 10^{59}$ erg (Nulsen & Bohringer 1995); turbulence and magnetic fields probably boost this by a factor of order unity (Eilek 1997). We can measure the energy losses from this region directly. The total luminosity in the emission line clouds is $P_{EL} \sim 10^{42}$ erg/s (Sparks *et al*). The bolometric radio power is $P_{rad} \sim 10^{42}$erg/s (Herbig & Readhead 1992). The X-ray luminosity of this region is $P_X \sim 1.5 \times 10^{43}$ erg/s (scaling the full X-ray excess, from Peres & Fabian 1997, to this inner region). The overall radiative loss time is thus $\sim 300$ Myr. In Eilek (1997) I argued the turbulent decay time $\sim 20 - 100$ Myr. There must be an ongoing energy resupply to offset these rapid losses.

The conventional picture is that this energy is supplied by the slow release of gravitational potential energy in a cooling inflow. However, the complex nature of the Virgo core is clearly inconsistent with a simple cooling flow picture. We have two other power sources. One is the radio jet itself, which puts out $P_b \sim 10^{43} - 10^{44}$ erg/s (§2.3). This input alone is comparable to the total radiative losses from the region. Another important driver is large-scale mass motions in the Virgo cluster. I argued above that the inner X-ray ridge (Harris 1997) may be evidence that some of this energy is transmitted to the core. Only a slightly transonic flow, $\mathcal{M} \sim 1.1$, is needed to account for the X-ray excess in this region (using data from Feigelson *et al* 1987 and from Harris 1997). Such a flow, driving a bow shock on an scale $R \sim 20$ kpc powers the core at $P_{flow} \sim \rho v^3 R^2 \sim 3 \times 10^{43}$ erg/s. This is strikingly similar to the energy provided by the radio galaxy, and again supports the picture of the Virgo core being an active and interesting region.

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