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M87 AT 90 CENTIMETERS: A DIFFERENT PICTURE

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ABSTRACT

We report new radio imaging of the large-scale radio structure of M87 with the VLA at 90 cm. These new images show the complex structure of the radio emission more clearly than previous attempts, some of which date back to the 1940s. The images suggest that the outward flow from the M87 nucleus extends well beyond the 2 kpc jet. Two "bubbles" of synchrotron emission appear to be inflated by this flow. A simple model of the emission, combined with our knowledge of the inner jet, suggest that the energy input into this region from the M87 nucleus exceeds the energy being radiated away as X-rays. This argues that the region within 40 kpc of the center of M87 is currently dominated by energy input from the M87 nucleus. The gas in the region is expanding, not flowing inward as is envisioned in the cooling flow model.

Subject headings: cooling flows — galaxies: active — galaxies: clusters: individual (Virgo) — galaxies: individual (M87) — galaxies: jets — radio continuum: galaxies

1. INTRODUCTION

M87 is one of the most famous radio galaxies, mainly because of studies of its nonthermal jet and activity in its nucleus. However, most of the radio emission responsible for its discovery in the 1940s (Bolton, Stanley, & Slee 1949) comes from a much larger scale with a projected end-to-end length of about 80 kpc (Mills 1952; Baade & Minkowski 1954). The large-scale structure has been studied more recently (Feigelson et al. 1987; Kassim et al. 1993; Böhringer et al. 1995; Rottmann et al. 1996). Nevertheless, the connection of the larger radio structure to the jet and the inner lobes has remained obscure.

M87 sits at the center of the X-ray–luminous atmosphere of the Virgo Cluster (Fabricant, Lecar, & Gorenstein 1980). The X-ray atmosphere has a simple, apparently undisturbed, morphology with a central luminosity peak. This atmosphere has been interpreted as a cooling flow (Stewart et al. 1984), but the situation may be more complex (Binney 1999). In addition, the inner region of the X-ray atmosphere has an unusual structure (Böhringer et al. 1995; Harris et al. 1999). Once again, the connection of the radio source to the X-ray atmosphere has remained obscure.

In this paper we report new 90 cm observations with the VLA of the large-scale radio emission with much higher dynamic range and resolution than have been achieved previously. Based on these new data, we propose that the radio halo is alive, rather than being a relic of some previous activity, and it is interacting strongly with the inner regions of the cluster's X-ray atmosphere.

2. OBSERVATIONS AND RESULTS

The observations were made over a period of many years with the VLA in spectral line mode. The earlier data come from dual-frequency observations at 74 and 321 MHz in the A, B, and C configurations. Images from these data were encouraging, so the bulk of the data in the current image were collected in the 1998 A and B arrays at 321 and 327 MHz, also in the spectral line mode. The use of narrow channels of 0.1 MHz or less reduced the systematic instrumental errors, which often limits such observations, and the radial smearing of the confusing sources, which makes them easier to remove and scatters less real power into the noise. It also facilitates editing of intermittent, mainly external, narrowband interference.

The observations used 3C 286 for initial amplitude and phase calibration and to set the standard VLA flux density scale, which derives from Baars et al. (1977). The entire field was imaged using the AIPS program IMAGR in 3D mode and self-calibrated using CALIB. The confusing sources were then subtracted from the UV data, and the remaining imaging and calibration was performed on just the central field containing M87. Further editing, imaging, and self-calibration were then carried out. The final image was produced using the maximum entropy program VTESS. In Figure 1 we show the resulting image as a false-color representation of the full image. In Figure 2 we show a gray-scale blowup of the central region showing the complex structure of brighter features more clearly. In Figure 3 we show a gray scale of the full source as well as the locations of minimum-pressure measurements discussed later in the paper.

Several features of this image are striking.[2] The very inner region (which appears as the red-orange patch in the center of Fig. 1) contains the well-known jet, which points to the northwest. This inner region (or inner "lobes") extends about 2 kpc from the core. Two collimated flows emerge from this region, one directed almost exactly eastward and the other directed slightly north of west. The initial direc-

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[2] See also Klein (1999) for an overall description of the Virgo A halo.

tion of the westward flow is roughly aligned with the direction of the inner jet, although the flow quickly bends and twists once it leaves the inner region. The flows appear to consist of a mass of bright, curved structures, which we call filaments. The eastern flow ends in a well-defined pair of edge-brightened circular lobes. This ear-shaped structure is reminiscent of a subsonic vortex ring. The western flow develops a gradual but well-defined southward twist, starting only a few kiloparsecs beyond the inner lobes. Finally, both flows are immersed in a larger structure that might be described as two overlapping "bubbles," each extending about 40 kpc from the nucleus. The coherent flows appear to be continuous from the point at which they emerge from the inner lobes to the outer edge of the radio halo. After reaching the halo, the flows gradually disperse, the westward flow particularly, and appear to be filling the entire halo with radio-loud, filamented plasma.

As can be seen in Figure 1, the bubbles end abruptly, with well-defined outer boundaries that are slightly limb brightened around perhaps half of the periphery. The brightest filaments stand out clearly from the general emission, suggesting higher minimum pressures than average over the source.

The results of minimum-pressure analysis for the magnetic fields and relativistic particles in the filaments are given in Table 1 as calculated at the positions indicated in Figure 3. We have assumed a frequency range of 10 MHz to 10 GHz, a spectral index $\alpha = 1.0$ ($S \propto \nu^{-\alpha}$), a proton-to-electron energy ratio $k = 1$, and that the factor $\zeta\phi = 1$, where ζ is the ratio of the true magnetic pressure to $B^2/8\pi$ and ϕ is the fraction of the volume occupied by relativistic electrons that is also occupied by magnetic field. For the geometry of each feature we have assumed a cylinder parallel to the line of sight with a radius equal to the VLA clean beam FWHM and a length equal to the projected width on the sky (W). We take a distance of 17 Mpc, so that $1''$ corresponds to 85 pc.

In Table 2 we give estimated values of the density, temperature, and pressure from Nulsen & Böhringer (1995) scaled to our assumed distance of 17 Mpc. Comparison of Tables 1 and 2 shows that all the filaments have somewhat lower minimum pressures than the surrounding thermal

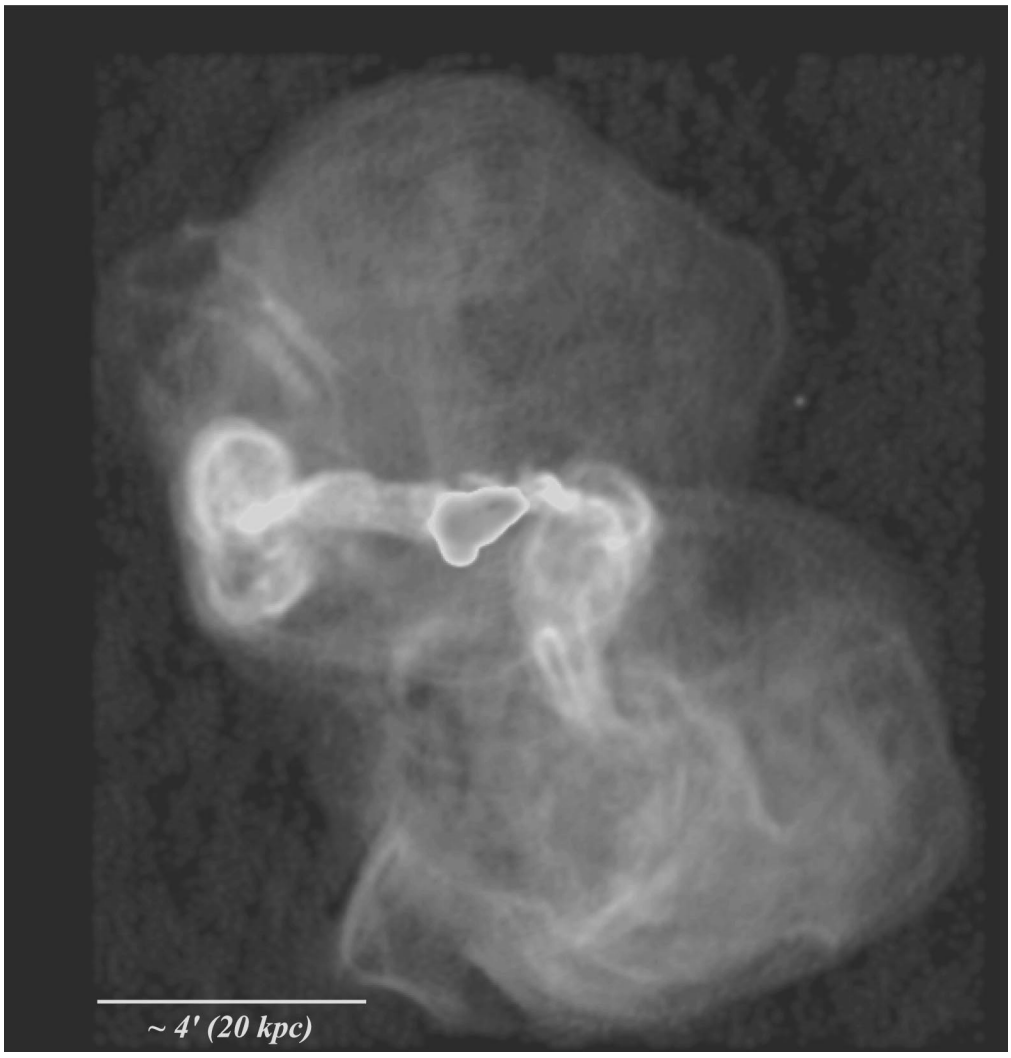

FIG. 1.—90 cm image of M87. The central region containing the jet and inner radio lobes is in the red-orange region near the image center. The convolving beam for this maximum entropy image is $7''.8 \times 6''.2$, P.A. = 86°. One arcsecond corresponds to 85 pc at our assumed distance of 17 Mpc.

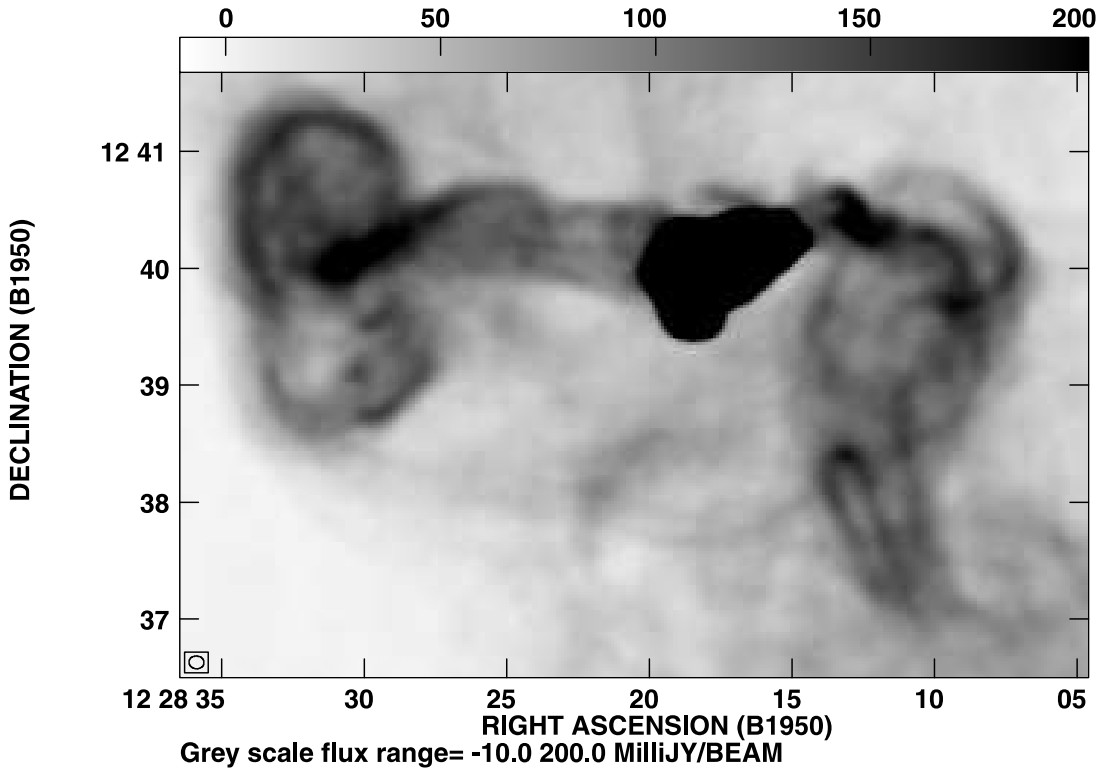

FIG. 2.—90 cm image of central part of Virgo A/M87 radio halo shown in Fig. 1. This display shows the sharp surface brightness drop between the inner radio-lobe structure (which contains the galactic nucleus and the well-known jet; solid black in this figure) and the east and west outflows that emerge from the inner lobes.

gas. If the filling factor $\zeta\phi$ is near 1, then the more diffuse regions of the source have minimum pressures of an order of magnitude below the thermal pressures. This could imply that the synchrotron emitting regions are far from the minimum-pressure case, that the filling factor of the emitting regions is much less than 1, or that the thermal gas is mixed with synchrotron emitting regions and provides much of the pressure inside the filaments.

3. PHYSICAL PICTURE: THE RADIO SOURCE

Virgo A does not fit neatly into the morphologies usually assigned to radio galaxies. It is clearly not an FR II galaxy because it does not have outer hot spots. This has led people to describe it as an FR I galaxy. While it may fit the strict definition of an FR I galaxy (being brightest closest to the core), it has little in common with most FR I radio galaxies. Type I sources generally contain coherent jets that slowly become wider and fainter the farther out one looks from the parent galaxy nucleus. Virgo A, at least as we see it projected on the sky, does not match this description.

We suspect that Virgo A is more closely related to a class of amorphous, steep-spectrum sources (e.g., Burns 1990), which are found only in dense cores of galaxy clusters. We are aware of several comparable radio sources, e.g., in A133, A2052, A2626 (Rizza et al. 2000), and A2199 (Owen & Eilek 1998); all are attached to central dominant galaxies in

TABLE 1

MINIMUM-PRESSURE ANALYSIS FOR M87 HALO FEATURES

Feature	Θ_{proj}[a] (arcsec)	D_{proj}[b] (kpc)	$f(\nu_0)$[c] (mJy beam^{-1})	W[d] (arcsec)	$B_{min\ p}$[e] (μG)	$p_{min\ p}$[f] (10^{-11} dyn cm^{-2})
A	210	18	25.0	24.5	7.48	0.52
B.....	203	17	52.9	15.4	10.6	1.0
C	68	5.8	58.8	41.4	8.22	0.62
D	115	9.8	70.6	33.3	9.19	0.78
E.....	157	13	13.8	8.8	8.46	0.66
F.....	177	15	24	14	8.70	0.70
G	255	30	28.4	19	8.38	0.65
H	334	28	20	26	6.90	0.44

[a] Θ_{proj} is the angular projected distance of the feature from the core.
[b] D_{proj} is the linear projected distance of the feature from the core.
[c] $f(\nu_0)$ is the surface brightness of the feature.
[d] W is the width (approximately the full width at zero power) of the feature.
[e] $B_{min\ p}$ is the field from the minimum-pressure solution.
[f] $p_{min\ p}$ is the pressure from the minimum-pressure solution.

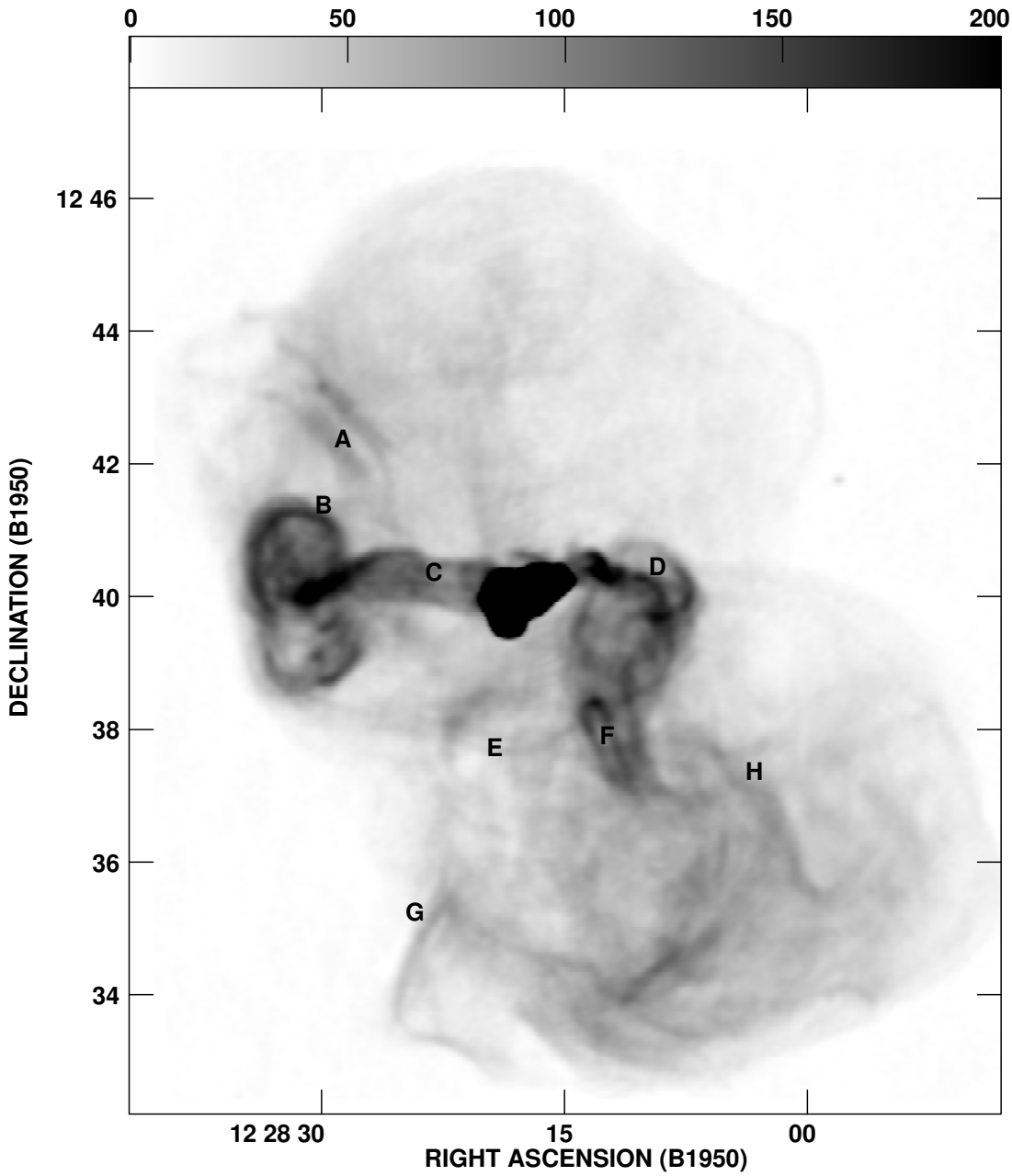

FIG. 3.—Gray-scale image of Virgo A/M87 and the location of minimum-pressure measurements given in Table 1

TABLE 2

X-RAY DENSITY AND PRESSURE PROFILE

Scale (arcmin)	Distance (kpc)	n_e (10^{-3} cm^{-3})	k_BT (keV)	p (10^{-11} dyn cm^{-2})
0.83.....	4.1	82.4	1.10	14.5
1.67.....	8.2	32.6	1.14	5.95
2.50.....	12.3	18.7	1.41	4.27
3.33.....	16.4	14.7	1.36	3.20
4.17.....	20.6	11.3	2.3	4.17
5.0	24.7	9.06	2.0	2.89
5.83.....	28.8	7.53	1.7	1.99
6.67.....	32.9	6.56	1.6	1.67

NOTE.—Data from Nulsen & Böhringer 1995, scaled to our assumed distance of 17 Mpc.

strong cooling cores. The fact that all such sources are found in a special position relative to their parent cluster (as well as their parent cluster being special in having a strong cooling core) argues against them being simply normal, FR I tailed sources seen in severe projection. It seems more likely that the interaction of the jet with the dense, high-pressure external medium is more extreme than in most radio galaxies and that the jet is bent or disrupted as it tries to flow through the dense external medium. The Virgo A radio halo is our best opportunity to study such an interaction.

3.1. *Nature of the Halo*

The M87 radio halo, Virgo A, looks like two bubbles that are supported by the energy of poorly collimated outflows

from the core. Three observations support this idea. First, the radio halo is the same size at all observed frequencies, from 74 and 330 MHz (Kassim et al. 1993) to 10.6 GHz (Rottmann et al. 1996). Second, the outer boundary is relatively sharp and is slightly limb brightened over about half of its circumference. Third, the new images show what seem to be two directed outflows that connect the inner jet and inner lobes to the full scale of the halo.

From this evidence we can immediately eliminate two possible models. The halo is not due to single-particle diffusion through the cluster gas (as in Andernach et al. 1979; Dennison 1980; De Young, Condon, & Butcher 1980). Such a picture predicts the size would depend on frequency because of synchrotron aging. Nor is the measured size of the halo limited by fading surface brightness in a simple outflow, as in many FR I radio tails. This hypothesis would again predict frequency-dependent sizes and also disagrees with the sharp rise at the edge, described in § 2.

It is also apparent that the halo region is inhomogeneous. The halo plasma is highly filamented. The radio-loud filaments can be regions with high field strength, high relativistic particle density, or both. We cannot uniquely describe the interfilament regions. They could simply be low-field, or low particle density, regions. Alternatively, they could be regions dominated by thermal plasma from the cluster atmosphere. Despite the fact that the outer edge of the radio halo is sharp and well defined, there is no strong evidence of a "hole" in the X-ray image.[3] This suggests that the X-ray–loud plasma has managed at least partially to penetrate the halo region.

We draw an important conclusion from the image—the halo is not simply a relic of previous activity (as in Turland 1975). Rather, it is currently "alive." It is being supplied with energy and relativistic plasma that ultimately come from the active nucleus and innermost radio jet of M87. The well-directed inner jet has been disrupted on a scale of a few kiloparsecs, but its mass and energy continue to flow out in "plumes" that are less ordered, less well confined, than the flow interior to the disruption.

We emphasize that this system cannot be static. Continuing energy input from the radio jet must cause the radio halo to expand outward, into the cluster gas. We propose the following model of the system. The radio halo is rather like a bubble, with a well-defined outer edge that separates the internal, radio-loud plasma from the external, thermal cluster gas. As the jet pours energy into the halo, the pressure in the halo will rise, forcing it to expand into the surrounding cluster gas. The observations show that the halo is in approximate pressure balance with the surrounding cluster gas; there is no evidence from the radio that the halo is overpressured, and an underpressured region would quickly collapse. Thus, we can model the expansion by assuming that the halo pressure remains comparable to the external pressure (as in Eilek & Shore 1989). We will show in § 3.2.2 that the expansion is slow and subsonic, so that the outer edge should not involve any shock structures.

A comment on the inner halo is in order. The inner halo (Turland 1975; Hines, Owen, & Eilek 1989) is a small, bright region approximately contiguous to the jet and extending only ~ 3 kpc from the galactic core. Previous workers have assumed that the inner halo is the only active region of the source. There is, indeed, a sharp drop in surface brightness between the inner and outer halos, making imaging of the transition very hard. However, there is no observational evidence for a well-defined outer edge to the inner halo such as there is for the outer edge of the outer halo.

We thus differ with recent models of M87 (Bicknell & Begelman 1996; Reynolds et al. 1996), which assume that the inner halo traps all of the energy coming through the jet. We can imagine two possibilities for the inner halo.[4] One is that it is a quasi-steady part of the flow, resulting from some choking of the flow that leads to a high-pressure, radio-bright inner region. If this is the case, the inner halo must be a porous structure, with most of the jet power flowing through it to the outer halo. Another possibility is that the inner halo is a recent transient, short-lived compared to the outer halo (which we show in § 3.2.2 is ~ 100 Myr old), possibly because of a recent change in the activity level of the core. If this is the case, it may have trapped a significant part of the recent output from the jet and be acting like a small bubble within a larger bubble.

Returning to the outer halo and our picture of it as a large expanding bubble, what can we say about the details? The magnetic fields and relativistic particles have minimum pressures somewhat less than the thermal gas. However, the uncertainties in such analyses, especially the filling factor of the synchrotron emitting plasma, allow the possibility of a much larger relativistic component. Thus, there are two possible models for what we are seeing, depending on whether the region is dominated by thermal or relativistic pressure.

3.1.1. *Relativistically Dominated*

It is possible that the synchrotron-emitting regions are far from the minimum-pressure case, with either the field or the relativistic particles strongly dominating. This can happen if the radio-loud region is inhomogeneous on scales smaller than the resolution of our image (that is, if the radio-loud plasma has a small filling factor within our resolved filaments) or if the relativistic protons carry much more energy than do the relativistic electrons. It can also happen if the region is simply dominated by pressure from one of the components, either relativistic particles or magnetic field. If this is the case, then Virgo A is primarily a relativistic bubble. The boundary apparent in the images is between the primarily relativistic, radio-loud plasma and the thermal plasma farther out in the cluster. The ongoing energy input to the plasma within this region will drive an expansion of the entire bubble.

If this is the case, thermal material inside the bubble must come from leakage through the boundary over the period of expansion. We are reminded of the semiporous nature of the terrestrial magnetopause, which allows partial penetration of the solar wind through local, intermittent magnetic reconnection. If this is the case, the mixing of thermal and relativistic plasma internal to the halo is most likely macroscopic, resulting in relativistic, radio-loud filaments with

[3] There is a weak feature apparent in the ringed X-ray flux at ~ 50 kpc, suggestive of some interaction; we have found this in archived *ROSAT* data, and it can also just be seen in the density profile from Nulsen & Böhringer (1995).

[4] We defer quantitative discussion of the inner-outer halo connection to a future paper.

only low thermal gas density, surrounded by interfilament regions dominated with thermal gas.

3.1.2. *Thermally Dominated*

It is also possible that the synchrotron emitting regions are close to the minimum-pressure case. The results of the minimum-pressure analysis, taken at face value, are most consistent with a thermally dominated model. In order to maintain pressure balance with the X-ray atmosphere, the emitting regions must contain a significant amount of thermal gas. If this is so, the emitting regions represent only a small fraction of the total energy inside Virgo A. In this case the jet must deposit its material and energy directly in the thermal material. This picture requires more effective mixing, on the microscopic scale, of the relativistic radio-loud plasma and the ambient thermal plasma.

If this is the case, the simple expanding bubble model can still describe the more complex physical processes that are taking place. One possibility is that the jet is depositing its matter, and energy, on scales $\sim$tens of kiloparsecs from the core in the form of turbulence and heat. Some of the turbulent energy may then be transformed into magnetic energy through the turbulent dynamo process. The heated thermal gas will expand to maintain balance with the unheated intergalactic medium outside this region. Thus the bubble is formed. The well-defined edge seen in the images is then the interface between the heated, expanding, mixed thermal-relativistic gas, and the undisturbed X-ray atmosphere ahead of the expansion surface.

3.2. *A Simple Dynamical Model*

Whichever picture best describes the M87 halo, the energy input into the bubbles comes from the energy carried in the outflow from the nucleus. We can use a simple model to describe the dynamics and estimate the age of Virgo A. Following our analysis of A2199 (Owen & Eilek 1998), we model Virgo A as a single spherical bubble with a steady energy input given by P_j, the total energy flux from the nucleus and jet. We assume that the bubble is in approximate pressure balance with the ambient medium and expands due to its internal energy. This system can be analyzed through simple energetics without needing detailed knowledge of the composition of the plasma inside the bubble.

3.2.1. *Jet Power*

We do need to estimate the jet power, however. This is easier to do for M87 than for more distant, less well-studied radio sources. The total flux of usable energy carried by matter in a relativistic jet is (e.g., Bicknell & Begelman 1996)

$$P_j = \pi r_j^2 v_j [\gamma_j(\gamma_j - 1)\rho_j c^2 + 4\gamma_j^2 p_j] , \qquad (1)$$

if p_j, ρ_j, γ_j, and v_j describe the jet pressure, mass density, Lorentz factor, and velocity, respectively. We do not know enough about the jet in M87 to estimate a good value for P_j, but we do know enough about the jet to estimate its minimum value $P_{j,\,\mathrm{min}}$. We do this by considering only the internal pressure in the jet plasma, which can be constrained by observations. We thus ignore both the plasma inertia, $\rho_j c^2$, and any magnetic field exceeding that corresponding to the minimum-pressure measurement. (Bicknell & Begelman 1996 also argue from their specific instability models that $\rho_j c^2 \lesssim 4p_j$.)

The flow velocity in the inner jet, on scales $\lesssim$2 kpc, is very likely relativistic, with $\gamma_j \sim$ 3–5 (Biretta, Zhou, & Owen 1995). We can thus estimate $v_j \sim c$ and $\gamma_j \gtrsim 3$. The jet radius can be measured directly from high-resolution images, such as in Owen, Hardee, & Cornwell (1989, hereafter OHC). The jet pressure cannot be found directly, but we can use the minimum pressure derived from radio and optical observations. Biretta, Stern, & Harris (1991, hereafter BSH) derive minimum pressures by assuming the jet is uniformly filled with radio-loud plasma. Alternatively, OHC argue that the radio emission comes from thin helices on the surface of the jet; this small volume gives them minimum-pressure values several times higher than given by BSH. (Their model would require a comparable pressure throughout the jet in order to maintain a stable structure.) We can thus use the BSH value to estimate the minimum likely P_j, noting that it may be higher. For knot D, we measure a radius of 22 pc; BSH give $p_{\mathrm{min}} \simeq 5.3 \times 10^{-9}$ dyn cm^{-2}, and OHC give $p_{\mathrm{min}} \simeq 1.2 \times 10^{-10}$ dyn cm^{-2}. For knot A, we measure a radius of 62 pc; BSH give $p_{\mathrm{min}} \simeq 3.5 \times 10^{-9}$ dyn cm^{-2}, and OHC give $p_{\mathrm{min}} \simeq 1.5 \times 10^{-10}$ dyn cm^{-2}. These result in a minimum jet power $P_{j,\,\mathrm{min}} \sim 7.8 \times 10^{43}$ ergs s^{-1} at knot D and $\sim 4.7 \times 10^{44}$ ergs s^{-1} at knot A. We conclude that a conservative estimate of the jet power is $P_j \sim$ few $\times 10^{44}$ ergs s^{-1}, and we use this to scale our modeling in what follows.

Finally, we compare this to the total power radiated by M87. The total radio power of the source is 9.6×10^{41} ergs s^{-1} (10 MHz–150 GHz, scaled to 17 Mpc distance; Herbig & Readhead 1992). This is not the total luminosity, however; the jet is a strong optical and X-ray source. From BSH we estimate the total jet power to be $\sim 2.8 \times 10^{42}$ ergs s^{-1}; giving a total luminosity of $\sim 3.7 \times 10^{42}$ ergs s^{-1} for M87. Interestingly, this is $\sim$1% of our conservatively estimated jet power, which is consistent with the general picture of radio galaxies as low-efficiency radiators.

3.2.2. *Expansion and Age of the Outer Halo*

We picture the halo as a region of hot plasma undergoing steady energy input from the jet at rate P_j. Let the halo plasma have adiabatic index Γ, pressure p, volume V, and internal energy U_{int}. Radiative losses from the halo are L_{rad}. Energy conservation tells us that the expansion is governed by (Eilek & Shore 1989)

$$\frac{dU_{\mathrm{int}}}{dt} = P_j - p\,\frac{dV}{dt} - L_{\mathrm{rad}} . \qquad (2)$$

If L_{rad} is small compared to P_j (as is true for M87), this relation can easily be solved for $V(t)$. To be specific, we assume that the halo is a spherical bubble of radius R, containing plasma with adiabatic index Γ, expanding due to its own internal energy. In a slow expansion, during which the pressure of the bubble does not greatly exceed that of the surroundings, we can make the approximation that the interior pressure remains comparable to the exterior pressure. If the exterior pressure decays with radius, the governing equation becomes

$$4\pi R^2 p_x(R)\,\frac{dR}{dt} = \frac{\Gamma - 1}{\Gamma}\,P_j . \qquad (3)$$

The X-ray data, summarized in Table 2, can be represented as $p(r) \simeq 4.3 \times 10^{-11}(r/r_0)^{-0.8}$ dyn cm^{-2}, with $r_0 = 12$ kpc.

Using this in equation (2), we find

$$\frac{4\pi}{2.2}\frac{\Gamma}{\Gamma-1}\,p_0 r_0^{0.8} R^{2.2} = P_j t\ . \tag{4}$$

We scale the jet power to 10^{44} ergs s^{-1}. We take $R \sim 35$ kpc as the current size of the source.[5]

Details of the expansion are sensitive to Γ, the internal adiabatic index. The two possibilities are $\Gamma = 5/3$, which describes a nonrelativistic plasma (assuming most of the plasma in the bubble is thermal), and $\Gamma = 4/3$ (appropriate if the bubble is dominated by relativistic particles and magnetic field). The current age of the radio halo is $t \sim 96 P_{44}^{-1}$ Myr, if $\Gamma = 5/3$; this increases to $150/P_{44}$ Myr if $\Gamma = 4/3$. We can estimate the current expansion rate of the outer edge from equation (3). This gives $dR/dt \sim 100 P_{44}$ km s^{-1} if $\Gamma = 4/3$, and ~ 160 km s^{-1} if $\Gamma = 5/3$. For comparison, the sound speed in the external gas is $c_s \sim 400$ km s^{-1}, so that the expansion is subsonic. The internal energy of the bubble at time t is $U_{\rm int} = (2.2/3\Gamma) P_j t$. Thus, a fraction 0.44 of the total jet power goes to internal energy if $\Gamma = 5/3$; this fraction becomes 0.55 if $\Gamma = 4/3$. The rest of the jet power goes to pdV work (and a small fraction to radiation).

3.3. *Further Issues*

To summarize, we find that the radio halo is still alive rather than being a relic of previous activity. It is expanding at about one-quarter of the local sound speed and is significantly younger than the galaxy that hosts it. However, this is not the end of the story; several interesting questions remain unanswered.

What is the origin of the bright radio filaments? There are at least three possibilities. The first is that they are highly compressed regions, or shocks, in transonic turbulence. The second is that they are the intermittent magnetic flux tubes seen in MHD turbulence at even low turbulent Mach numbers (Kinney, McWilliams, & Tajima 1995). The third is that they are similar to the filaments seen in numerical simulations of passive-field radio sources (Clarke 1996). All three possibilities will lead to regions of high field and possibly high particle density, which will be bright in synchrotron radiation.

What is the nature of the "ear" at the east edge of the source? D. de Young (1998, private communication) pointed out to us that it resembles a subsonic vortex ring. This is an interesting possibility. Little is known about vortex rings in compressible, magnetized plasmas, but one might expect them to retain their basic characteristics. Its reason for existence, however, remains unclear. Further, are the east and west flows fundamentally different, so that one disrupts and one creates a vortex ring, or is the different environmental?

Is in situ electron acceleration necessary? In the bright filaments, with $B \sim 10\ \mu$G, electrons radiating at 1 GHz live only ~ 50 Myr, which is a bit less than the age of the halo. This result suggests either that the electrons undergo in situ reacceleration in the filaments or else that they spend most of their life in a weaker magnetic field, possibly in the interfilament region.

[5] The projected semimajor axis of the halo is 37 kpc, and the semiminor axis is 22 kpc. These are equivalent to a spherical volume of radius 30 kpc; we choose $R = 35$ kpc to allow for modest projection effects.

What is the nature of the outer edge, and how efficient is the mixing across it of external gas with radio-loud plasma? The X-ray profile, together with the apparent integrity of the radio edge, suggests there has been partial mixing. Should we look to the Earth's magnetopause for an analogy (where patchy reconnection allows some fraction of the incoming plasma to mix across the boundary)? This may be a good analogy if the edge of the bubble is defined by a quasi-parallel magnetic field. Alternatively, should we look to the outer edges of old supernova remnants (which have highly filamented outer shells, and are thus more "open" to mixing with the ambient gas)? This may be a better analogy of the edge of the bubble is governed by fluid, not magnetic, processes.

Finally, why is this radio galaxy so unusual? Most radio galaxies at this power are supported by jets that remain collimated and directed for scales $\sim$10–100 kpc. However, the M87 jet continues undisturbed for only a few kiloparsecs. What is the reason for the jet disruption so close the galactic center? Is it connected somehow to the dense cooling core in which the source sits and to the existence of a small set of amorphous central radio galaxies in other, similar, cooling-core clusters?

4. PHYSICAL PICTURE: THE CLUSTER CORE

The Virgo X-ray halo is smooth, centrally peaked, and nearly circular (ellipticity ~ 0.1 on large scales; Fabricant & Gorenstein 1983). Using spherical deprojection of *ROSAT* data (also Table 2 in Nulsen & Böhringer 1995), one derives densities and temperatures that suggest the cooling time is less than the Hubble time for the inner ~ 80 kpc. The smooth X-ray structure and short central cooling time have led various authors to suggest that M87 sits in the center of a modest cooling flow. In the simple cooling-flow model radiative losses are balanced by slow settling of the gas in the cluster gravitational potential (e.g., Fabian 1994). For M87, the cooling inflow has been estimated as $\dot{M} \sim 24\ M_\odot$ yr^{-1} (e.g., Peres et al. 1998, again scaled to 17 Mpc). Such a smooth, spherically symmetric inflow, with the densities given in Table 2, will be very slow; it will have inflow velocity ~ 2 km s^{-1} at 50 kpc.

4.1. *Activity in the Core*

Consideration of the radio data shows that the picture is more complex than a simple cooling-driven inflow. This is demonstrated by several pieces of evidence.

The radio image itself shows evidence of a disturbed inner halo. The filaments suggest both directed and disordered flows. These flows are magnetized and possibly transonic (which we suggest based on the enhanced radio emission from the filaments, which are probably regions of strong magnetic field).

High-resolution X-ray data (Feigelson et al. 1987; Nulsen & Böhringer 1995) show complex structure in the inner ~ 20 kpc of the X-ray–emitting gas. This gas has a very asymmetric distribution, with approximately the same extent as the radio halo. In addition, new work by Harris et al. (1999) shows that the X-ray excess is enhanced in a narrow ridge that crosses the jet close to knot A, the brightest knot in optical and radio. This strongly suggests that the jet and the X-ray gas are interacting on this scale.

The dynamic radio halo is being supplied with energy from the jet. It should be expanding outward, into the

thermal gas, driven by its own internal energy. Our simple model predicts an expansion speed ~ 100 km s^{-1}, which is approximately one-quarter of the local sound speed. This must have an impact on the ambient cluster gas.

The inner few kiloparsecs of M87, at least, are magnetized and turbulent. Emission-line clouds embedded in the gas are moving at ~ 200 km s^{-1} (Sparks, Ford, & Kinney 1993; Keel, Owen, & Eilek 1996). It is very likely that these clouds share the velocity field of the hotter gas in which they sit. In addition, Faraday rotation data reveal dynamically significant, ordered magnetic fields in this region (Owen, Eilek, & Keel 1990; Zhou 1998). The magnetic field is probably supported by transonic turbulence (Eilek, Owen, & Zhou 1999). Taken together, these observations suggest that the very inner part of the M87 halo is turbulent, probably at transonic levels.

4.2. *Energetics and Activity*

The evidence shows that the Virgo core is a complex place. On scales $\lesssim 40$ kpc it contains a dynamic mixture of relativistic particles, thermal plasma, and magnetic fields. We suspect that the entire halo is similar to the inner few kiloparsecs, being turbulent and magnetized at significant levels.

It follows that this region cannot be described as a simple cooling flow. This can be demonstrated by basic energetics. The bolometric X-ray luminosity from the region occupied by the radio source, roughly the central 40 kpc, is $L_X \sim 0.9 \times 10^{43}$ ergs s^{-1}. (To derive this, we use the densities and temperatures from Table 2, with the cooling curve given by Westbury & Henriksen 1992.) The central cooling can also be found using the value given by Peres et al. (1998) for L_X within cooling core, scaling that value to 17 Mpc and then using the deprojected density structure from Table 2 to find the luminosity within 40 kpc. In the absence of a comparable energy input, the central gas must indeed cool and collapse in the gravitational well of the system.

However, the picture is not so simple for Virgo. The black hole in the galactic nucleus is currently supplying $P_j > 10^{44}$ ergs s^{-1} to the radio halo. Only a small fraction of this is leaked to radio emission. The bulk of this energy must be deposited in kinetic or internal energy of the composite plasma in the Virgo core. This input is at least as large as, and probably much larger than, the radiative losses from the core. It follows that the region is more complex than a simple cooling flow. Binney (1999) has already pointed this out, and we agree with him.

What effects might we expect? The energy from the core is being deposited on a scale ~ 40 kpc throughout the radio halo. Some fraction of the jet energy will go to turbulence or bulk flows (such as the ~ 100 km s^{-1} expansion of the bubble), while the rest will go directly to heating. The heat will directly drive an outward expansion of the heated gas into the cooler, lower pressure gas sitting above it. The turbulence will enhance magnetic fields, through dynamo effects, which may in turn enhance the turbulence through magnetic buoyancy. We cannot predict the exact fraction of energy deposited in flows or in heat; recalling the energetics estimated in § 3.2.2, we might estimate that approximately half the energy goes into each mode.

The thermal state of the gas will be determined by all of these competing processes—heating, radiative cooling, thermal conduction, expansion, turbulence, and turbulent dissipation. X-ray data find a component of gas at ~ 1.1 keV in the inner arcminute, and warmer gas at ~ 3 keV outside of $\sim 3'$ (Fabricant & Gorenstein 1983; Nulsen & Böhringer 1995; Matsumoto 1999). Our simple arguments here cannot predict the full temperature structure of the core. Previous steady state, spherically symmetric models (Takahara & Takahara 1981; Tucker & Rosner 1983) provided interesting first attempts but also cannot address the complexity of the region. More detailed, time-dependent simulations will be required.

In the absence of full numerical simulations, simple lifetime considerations can be helpful. The current energy content within $\lesssim 40$ kpc is $U_{th} \sim 3 \times 10^{59}$ ergs (again using data from Table 2). If the jet maintains an average energy input of $10^{44} P_{44}$ ergs s^{-1}, we can expect something like half of that power to be deposited in the cluster gas, perhaps shared equally between direct heating and turbulence (which will eventually decay into indirect heating). It follows that it will take $\sim 190/P_{44}$ Myr to deposit an amount of energy comparable to that currently in the region. For comparison, the radiative lifetime of the region is $U_{th}/L_X \sim 1$ Gyr. Thus, based on our estimated lower limit for the jet power, its energy input clearly dominates radiative losses at present. We estimated in § 3.2.2 that the current age of the radio halo is $\sim (100\text{–}150)/P_{44}$ Myr. Thus, the radio halo is young compared to the age of the galaxy, but "just right" compared to the energy turnover times in the Virgo core.

This suggests to us an on-off duty cycle for the central engine in M87. The engine may have been active for only 100–200 Myr, which happens to be comparable to the energy turnover times for the core. As long as the engine remains active at its current level, it will have a strong effect on the local cluster core. It will heat the core and support turbulence, bulk flows, and magnetic fields in that core. These extra pressure sources will in turn offset radiative cooling, support the gas against gravitational infall, and possibly drive the central regions outward in a local expansion. Once the central engine turns off, the gas will cool and return to a quasi-static state as the turbulence and bulk flows dissipate. Binney & Tabor (1995) have simulated a similar situation for a smaller galaxy (with the differences that they assumed the energy was all deposited at the very center of the flow, and in their spherically symmetric model they could not include turbulent flows or magnetic fields). Their calculation shows the cyclic response of the ambient gas as it heats and cools, expands and collapses, in response to the activity cycle of the central energy source.

5. CONCLUSIONS

We have obtained new and wonderful radio images of Virgo A, the large-scale M87 radio halo. Our images clearly show that the halo is a complex and active object. Comparison of our data to recent X-ray images shows that the radio-loud and X-ray–loud plasmas are interacting strongly in the core of the Virgo Cluster. Simple energetics show that the input to the region, from the active nucleus in M87, exceeds radiative losses at the present epoch.

We thus arrive at a new picture of M87 and the Virgo Cluster. We find a competition for dominance between the slow, cooling-driven inflow of the hot cluster gas and the violent outflow of energy from the black hole in the galactic nucleus. At present the black hole appears to be winning in the inner region of the system. The detailed processes taking place on scales from a few kiloparsecs to 40 kpc are likely to

arise from this complex competition. However, both the timescales we have derived and the general wisdom about radio galaxy lifetimes suggest that the current outflow is likely to be transient. If the activity in the galactic nucleus diminishes or stops altogether, then the physical processes that can create a cooling flow would dominate. It may be that M87, like other central active galaxies in cooling cores, has gone through several heating/cooling cycles during its lifetime.

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