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LOW-FREQUENCY VLA OBSERVATIONS OF ABELL 754: EVIDENCE FOR A CLUSTER RADIO HALO AND POSSIBLE RADIO RELICS

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ABSTRACT

We present 74 and 330 MHz VLA observations of Abell 754. Diffuse, halo-like emission is detected from the center of the cluster at both frequencies. At 330 MHz, the resolution of 90″ distinguishes this extended emission from previously known point sources. In addition to the halo, and at a much lower level, outlying steep-spectrum emission regions straddle the cluster center and are seen only at 74 MHz. The location, morphology, and spectrum of this emission are all highly suggestive of at least one, and possibly two, cluster radio relics. Easily obtained higher resolution, higher sensitivity VLA observations at both frequencies are required to confirm the extended nature of the halo-like emission and the 74 MHz relic detections. However, since there is prior evidence that this cluster is or has recently been in the process of a major merger event, the possible discovery of relics in this system is of great interest in light of recent observational and theoretical evidence in favor of a merger-relic connection. We discuss the possible role that the merger shock waves, which are seen in the X-ray emission, may have played in the formation of the halo and radio relics in A754.

Subject headings: galaxies: clusters: individual (A754) — galaxies: halos — radiation mechanisms: nonthermal — radio continuum: galaxies — shock waves

1. INTRODUCTION

Clusters of galaxies are the most massive gravitationally bound objects in the universe that are in a state of quasi equilibrium. Our current understanding of structure formation suggests that clusters form via the merging of smaller entities, such as galaxy groups and small clusters. During a merging process, clusters are able to release considerable energy into particle acceleration via shock waves and turbulence (De Young 1992). The accelerated relativistic particles have a short radiative lifetime but can be reaccelerated by recurrent merger events. For several galaxy clusters, radio observations of relativistic plasma reveal the presence of extended (>500 kpc) diffuse emission that has a steep spectral index and no observable optical counterpart (Feretti & Giovannini 1996, and references therein). The synchrotron nature of the emission allows us to trace large regions of relativistic, charged electrons and magnetic fields within the X-ray–emitting intracluster medium (ICM). In general, this diffuse emission appears to fall within two categories: "halos," which are centrally located, regular in shape, and unpolarized, and "relics," which are located in the peripheral regions of the cluster, irregular in shape, and generally highly polarized (Feretti & Giovannini 1996).

The origin of these regions of diffuse emission is still a matter of great debate. The large physical scales involved, combined with the relatively short radiative lifetimes, suggest that the electrons must be reaccelerated within the ICM (Jaffe 1977). Theoretical models propose that this particle acceleration may occur in the turbulence and shocks associated with major cluster-merger events (De Young 1992; Tribble 1993; Feretti 1999; Brunetti et al. 2001), although alternative models include secondary particle production from proton-proton interactions (Dennison 1980) and particle diffusion from nearby head-tail galaxies (Giovannini et al. 1993). Recent work suggests that there is a positive correlation between the presence of radio halos and relics, and current (or recent) merger activity associated with clusters (Feretti & Giovannini 1996; Feretti 1999).

Clusters of galaxies contain a considerable fraction of hot plasma, the ICM, which is heated up to several 10^7–10^8 K because of virialization. This hot thermal plasma traces the gravitational potential of clusters and is thus an ideal tool for determining the dynamical state of a cluster. Because of its high temperature, which corresponds to several keV in energy, the ICM plasma is only directly observable with X-ray telescopes. The X-ray emission allows us to trace not only the potential but also the presence of nonuniform heating, which is caused by adiabatic compression or shock waves from merger events. This kind of heating, which was difficult to detect with past X-ray telescopes, is now observable in detail with the latest X-ray satellites, such as *Chandra* (Vikhlinin, Markevitch, & Murray 2001a, 2001b) and *XMM-Newton* (Arnaud et al. 2001).

In this paper we present new radio observations of the galaxy cluster Abell 754 (Abell, Corwin, & Olowin 1989), which was observed at 74 and 330 MHz with the NRAO VLA observatory.[7] X-ray observations of this cluster (Henry & Briel 1995; Henriksen & Markevitch 1996), which trace the thermal ICM, indicate that it is undergoing a violent merger event. Recent three-dimensional MHD/*N*-body simulations of Roettiger, Burns, & Stone (1999a) and Roettiger, Stone, & Burns (1999b) indicate that shocks and turbulence associated with the cluster merger could provide

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the magnetic field amplification and particle reacceleration necessary to generate diffuse radio-relic emission from regions of the ICM. Further, the energy input from the merger may accelerate relativistic particles in the cluster center to produce a radio halo. Therefore, A754 seems to be the ideal host for diffuse radio emission. However, up until now, radio observations have not been able to provide an unambiguous detection of such emission. Its detection is very important, since it strongly supports the hypothesis of a connection between radio halos/relics and merger activity.

1.1. *Past Observations of A754*

At a redshift of $z = 0.054$ (Bird 1994), A754 is a rich galaxy cluster, $\sigma_v = 900$ km s^{-1} (Zabludoff & Zaritsky 1995), which has been extensively studied in the optical, radio, and X-ray bands. Observations in the 0.5–10 keV *ASCA* band (Henriksen & Markevitch 1996) find an X-ray luminosity of 6.4×10^{44} h_{75}^{-2} ergs s^{-1} and an emission-weighted temperature of 8.5 ± 0.5 keV for this cluster. Maps of the X-ray surface brightness and X-ray temperature from *ROSAT* (Henry & Briel 1995) as well as X-ray temperature maps from *ASCA* (Henriksen & Markevitch 1996) show temperature variations that indicate that this cluster is going through or has recently gone through a violent merger event.

A754 has been the object of low-frequency radio observations for over 20 years. In no reported observation has a relic been detected, and evidence for a radio halo has been inconclusive. Extended emission was reported at 2.7 GHz (Wielebinski et al. 1977) and at 408 MHz (Mills, Hunstead, & Skellern 1978). In both cases, the resolution of 3′–4′ made it difficult to distinguish apparent extended flux from the blended images of point sources associated with galaxies in or behind the cluster. A higher resolution observation at 610 MHz (Harris et al. 1980) showed no extended emission, yet the authors concluded that it is likely that a halo exists, since, with just the point sources they detected, they were unable to account for all the emission previously reported at lower frequencies. This issue was later reinvestigated with the VLA in a B and C array observation (40 minutes combined) at 330 MHz (Giovannini, Tordi, & Feretti 1999; Giovannini & Feretti 2000). This observation detected no extended flux in the central regions of this cluster. We note, however, that the short integration times obtained at 330 MHz would provide very poor *u-v* coverage, which could easily lead to missing large-scale structure in the maps.

2. RESULTS

2.1. *The Data and Reduction Methods*

VLA C-array observations of A754 were conducted on 2000 March 21 simultaneously at 330 and 74 MHz. The observational parameters are summarized in Table 1. At both frequencies, observations were conducted in spectral line mode to reduce the effects of bandwidth smearing and to allow for more accurate and less costly radio-frequency interference (RFI) excision. Ultimately, 8% and 23% of the data were flagged at 330 and 74 MHz, respectively. Cygnus A was used as a flux density, bandpass, and initial phase calibrator, and we estimate the flux densities that we quote as accurate to ∼15%. Successive loops of self-calibration (AIPS task CALIB) and noncoplanar, wide-field image deconvolution (AIPS task IMAGR) were used to mitigate confusion and achieve maximum sensitivity in our images

TABLE 1

PARAMETERS OF THE VLA C-ARRAY OBSERVATIONS OF A754

Parameter	Frequency	
	330 MHz	74 MHz
Bandwidth (MHz)	3	1.5
Data type	128 channel 1 IF[a] RR & LL[b]	64 channel 1 IF[a] RR & LL[b]
Time on source (hr)	3	3
Restoring beam	90″ × 90″	316″ × 233″
rms sensitivity (mJy per beam)	6.5	200

[a] Intermediate frequency.
[b] Right-right and left-left polarization.

(Perley 1999). The realized rms sensitivities of ∼6.5 mJy per beam and ∼200 mJy per beam at 330 and 74 MHz, respectively, are both approximately 10 times higher than the expected thermal noise levels. We attribute the difference to a combination of confusion and poorly understood, broadband, mainly VLA-generated RFI, which especially affects low-frequency observations in the compact C and D configurations.

2.2. *The Radio Halo at* 74 *and* 330 *MHz*

Our 74 and 330 MHz images are presented as contours in Figures 1 and 2, respectively, while a 1.4 GHz image from the NRAO VLA sky survey (NVSS; Condon et al. 1998) is superimposed on Figure 1 as gray scale. At both frequencies, we detect extended emission in the central region

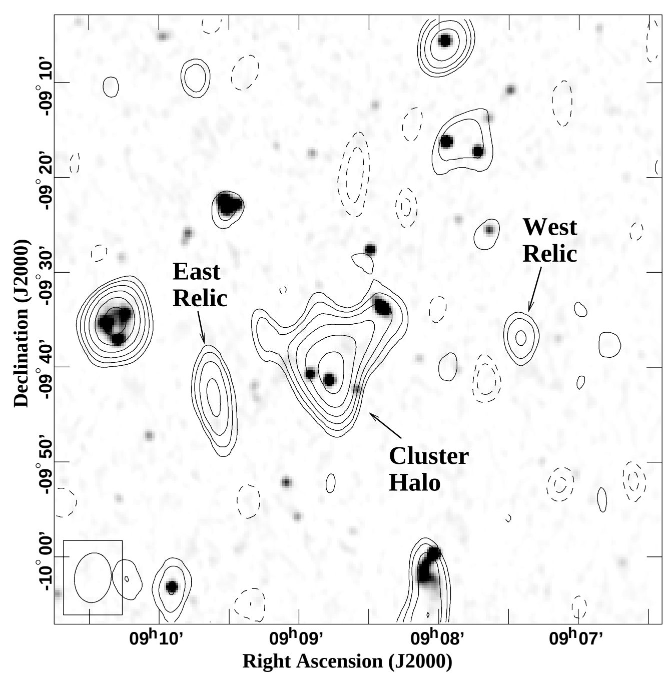

FIG. 1.—Contours of a 74 MHz VLA C-array image of A754. We identify the cluster radio halo and two possible radio relics. For comparison, we show the NVSS 1.4 GHz image in gray scale as well. For the 74 MHz image, the peak flux density is 4.2 Jy per beam and the beam size is 316″ × 233″ at a position angle of −7°. Contour levels are 0.4 Jy per beam times −1.4, −1, 1, 1.4, 2, 2.8, 4, 5.7, 8, and 11.3. The off-source rms noise is 0.2 Jy per beam.

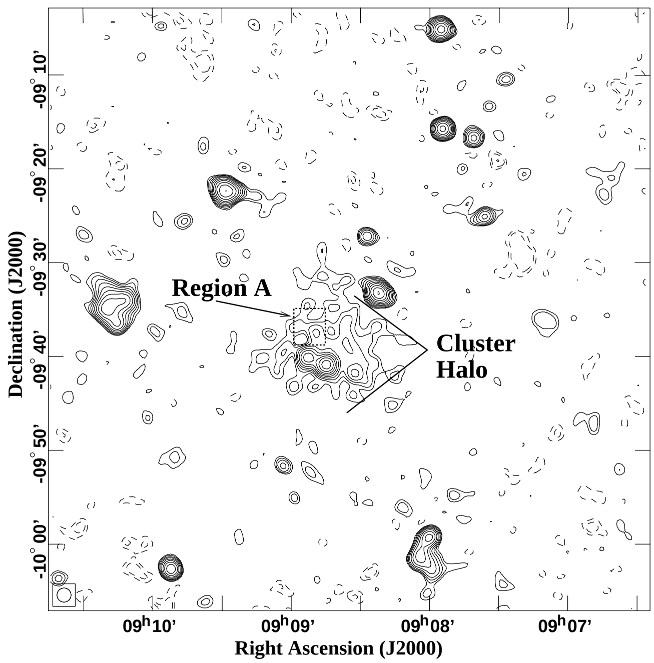

FIG. 2.—A754 at 330 MHz. This image was taken with the VLA in C-array and clearly shows what appears to be a radio halo. Also visible are four bright point sources in the halo region that also appear at 1.4 GHz. The spatial scale is identical to Fig. 1. The peak flux density is 567 mJy per beam and the restoring beam size is 90″ × 90″. Contour levels are 16 mJy per beam times −1.4, −1, 1, 1.4, 2, 2.8, 4, 5.7, 8, 11.3, 16, 22.6, and 32 . The off-source rms noise is 6.5 mJy per beam.

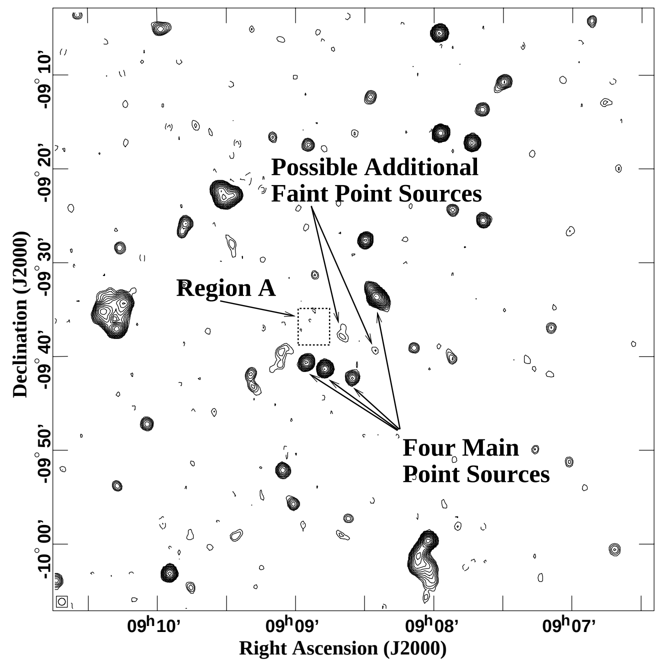

FIG. 3.—A754 at 1.4 GHz. This image was created from the NVSS catalog and is shown at the same spatial scale as Figs. 1 and 2. The point sources here provide a reference for comparison with the 330 MHz image. The peak flux density is 181 mJy per beam and the restoring beam size is 45″ × 45″. Contour levels are 1.4 mJy per beam times −1.4, −1, 1, 1.4, 2, 2.8, 4, 5.7, 8, 11.3, 16, 22.6, 32, 45. 3, 64, 90.5, and 128. The off-source rms noise is 0.45 mJy per beam.

of the cluster, which is consistent with a radio halo, although the 5′ resolution at 74 MHz is clearly too poor on its own to distinguish between genuine halo emission and a blend of point-source emission. However, analysis of the 74 MHz image in conjunction with information from the 330 MHz and 1.4 GHz data indicates that there is clearly excess 74 MHz emission beyond just a blending of the four main NVSS point sources in the halo region. To estimate their 74 MHz contribution, we determined their spectral indices between 330 MHz and 1.4 GHz and extrapolated these to 74 MHz. The prediction for the combined flux density of these four point sources at 74 MHz is 2.9 Jy, while we detect 7 Jy of emission at the cluster center. Therefore, we detect an excess of about 4 Jy of 74 MHz flux in addition to the point sources.

The case for extended emission is even stronger at 330 MHz (Fig. 2), where the resolution is sufficient to clearly separate the brightest point sources from the diffuse emission in the region. Apart from the four main point sources, we measure a total of 750 mJy of flux density in the region. Of course, it is possible that even this emission is made up of a blending of even more faint point sources in the center of the cluster that are undetected at 1.4 GHz, and close inspection of the NVSS image does suggest more faint point sources in the region (Fig. 3). However, there are regions of the halo that appear strongly at 330 MHz, but not at all at 1.4 GHz. If we examine region A, which we define in Figure 2, the fact that it has a peak flux density of 49 mJy per beam yet contains no observable flux at 1.4 GHz requires a spectral index of at least 1.5, $S_\nu \propto \nu^{-\alpha}$. Taking the halo as a whole, our estimates of 4 Jy at 74 MHz and 750 mJy at 330 MHz indicate a spectral index of $\sim$1.1. This is unusual for point sources associated with radio galaxies. The four brighter point sources all have spectral indices ranging from 0.5 to 1.0. We therefore assert that while some of this emission could be due to point sources, a significant fraction corresponds to a diffuse cluster radio halo with 3 σ major and minor axes of $\sim$450″ × 400″, respectively. At the redshift of the cluster, this corresponds to a scale of $\sim$430 × 380 h_{75}^{-1} kpc, a factor of 2–3 smaller than the largest known giant Mpc halos, but still not the smallest halo known (Feretti 1999). From our 330 MHz image we estimate the halo center at $\sim$ R.A. $09^{\rm h}08^{\rm m}43^{\rm s}$, decl. $-09°36′57″$, indicating that it is shifted westward of the X-ray maximum and also of the cluster center, which we place at $\sim$ R.A. $09^{\rm h}09^{\rm m}03^{\rm s}$, decl. $-09°39′46″$ with reference to an elliptical beta-model fit. We note that the inferred $\alpha = 1.1$ spectrum of the diffuse emission is consistent with previous estimates (Harris et al. 1980), although the total flux levels are still somewhat ($\sim$40%) lower than predicted.

Initially puzzling 330 MHz observations by Giovannini & Feretti (2000) at comparable rms noise failed to detect the halo emission. However, a plausible explanation emerges in light of the fundamentally different spatial characteristics of the two data sets. Our observations were 3 hr in the VLA C array, while theirs was a combination of B and C array snapshots (40 minutes total), with consequently less thorough *u-v* coverage. A possible explanation is therefore that their superior resolution, provided by B-array baselines, set a lower basic confusion level, and thus provided a nominal sensitivity comparable to our longer, lower resolution integration. However, their snapshot C-array *u-v* coverage would at the same time have been much less sensitive to the large-scale extended emission that we detect. Indeed,

TABLE 2

NEW OBJECTS IN A754 AT 74 MHz

		Position (J2000)	
Object ID	Peak (Jy per beam)	R.A.	Decl.
East relic	1.25	09 09 36	−09 43 22
West relic......	0.85	09 07 25	−09 36 52

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

imaging of a snapshot subsection of our own C-array data failed to detect the halo.

2.3. *Discovery of Radio Relics at* 74 MHz

Our 74 MHz image (Fig. 1) reveals two newly detected objects without counterparts at either 330 MHz or 1.4 GHz, which we label as the "east relic" and the "west relic" (see Table 2). While the 6 σ (integrated flux $\sim$1.45 Jy) and 4 σ ($\sim$850 mJy, unresolved) detections are weak, it is nevertheless highly unusual to detect sources at 74 MHz that are not also seen by the VLA at either 330 MHz or 1.4 GHz. In fact *all* other objects in a $4° \times 4°$ 74 MHz image that appear at the brightness of the fainter west relic or higher have clear counterparts in the 1.4 GHz NVSS images, and 330 MHz counterparts within the $\sim$2° radius region in which the 74 and 330 MHz fields of view overlap. This suggests an unusually high spectral index for these objects. In order to explain the lack of a detection at above 3 times the rms sensitivity in the 330 MHz or 1.4 GHz images, the east relic would need a spectral index of at least 1.8 or 1.4, respectively. Such high spectral indices are typical of cluster radio relics.

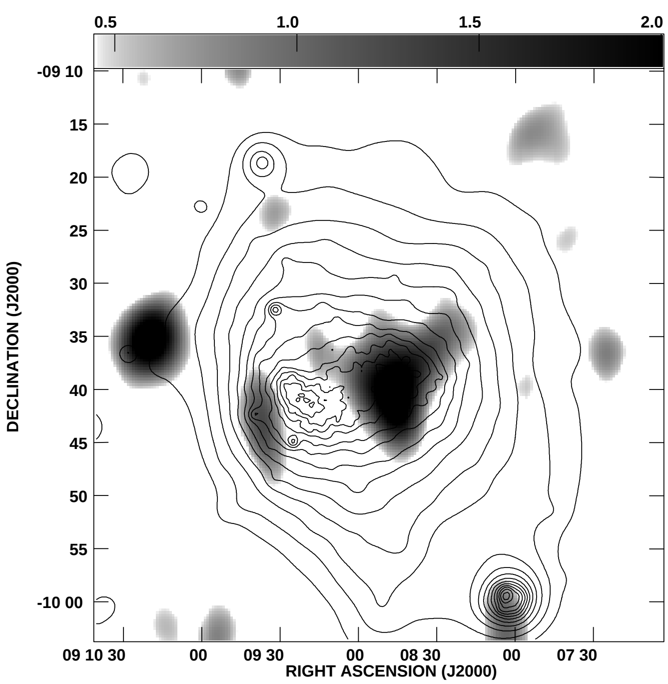

FIG. 4.—Overlay of 74 MHz VLA data in gray scale with the *ROSAT* 0.1–2.4 keV X-ray contours. The location of the east relic is coincident with the ram pressure compressed X-ray contours. Further, the radio-halo and -relic emission appear to avoid the dense X-ray bright region of the cluster. We note that there appears to be a compact X-ray source at the location of the east relic, but as of yet there is no optical identification for this object.

There is further evidence that these objects detected at 74 MHz are indeed radio relics. First, the morphology of the east relic, with an elongation perpendicular to its separation from the cluster X-ray maximum, is highly suggestive of a relic. Its major and minor axes are $\sim 600'' \times 230''$, respectively, which corresponds to scale sizes of $\sim 580 \times 220\ h_{75}^{-1}$ kpc at the redshift of the cluster. The reality of the mainly unresolved west relic is clearly much more speculative, although it is noteworthy that its location with respect to the cluster X-ray maximum is opposite to that of the east relic. An overlay of the positions of these relics with *ROSAT* hard X-ray data (Fig. 4) reveals that the east relic falls exactly at the location of flattened, compressed X-ray contours. Such a rapid gradient in X-ray surface brightness is expected at the location of merger shock waves. Further, Roettiger, Stone, & Mushotzky (1998) have predicted the locations of shock waves based on their model of the cluster merger in A754, and it is especially noteworthy that the location of the east relic coincides with a jump in the X-ray temperature predicted for the shock waves in this cluster. We note, however, that the signal-to-noise ratio for both of these new objects is still very low, and thus the objects (the west relic in particular) should be regarded with caution. We plan to undertake deep follow-up observations of these sources with the VLA at higher resolution to confirm these detections and provide tighter constraints on their spectra. Additional follow-up observations will be undertaken to identify the compact X-ray source located at the position of the east relic and to determine if the two objects are connected.

3. DISCUSSION

In the numerical model of Roettiger et al. (1998), a large subcluster (cluster to subcluster mass ratio of 2.5:1) has passed from east to west, slightly off-axis from the core of the A754 system. This merger event results in the formation of two shock waves, which are visible as temperature jumps in Figure 2*a* of their work. The eastern shock heats the infalling, stripped subcluster gas in a relatively small area. The location of this shock at the ram pressure–flattened edge of the X-ray peak is coincident with the observed location of the east relic source. The western shock heats the outer regions of the main cluster ICM and is much more extended. In principle, this shock could have caused the west relic, but we note that the west relic is farther away from A754's X-ray peak ($\approx 1.8\ h_{75}^{-1}$ Mpc) than the shock wave in the numerical model ($\approx 1.2\ h_{75}^{-1}$ Mpc). The measured (Henry & Briel 1995; Henriksen & Markevitch 1996) and simulated (Roettiger et al. 1998) temperature maps show that mainly the outer western region is heated by this shock wave, but not the innermost cluster core region.

The temperature variation suggests that the impact of the infalling gas, combined with the change in the gravitational potential of the primary cluster due to the core passage of the dark matter subcluster, was not violent enough to produce a shock wave in the dense main cluster core. The core was only compressed adiabatically, and relaxed nearly to its original temperature in a later merger stage. When the impact moved into outer, less dense regions, a shock wave was created that heated the gas nonadiabatically. Such emergence of outgoing shock waves is observed in numerical simulations of cluster-merger events (S. Schindler 2001, private communication).

A fraction of the energy dissipated in shock waves is often transferred into relativistic particle populations. Accelerated relativistic electrons have short radiative lifetimes ($\sim$0.1 Gyr) and should therefore produce the radio-relic emission close to the current location of the shock waves. The electron acceleration required to produce the relic emission could result from Fermi I diffusive shock acceleration of ICM electrons (Enßlin et al. 1998; Roettiger et al. 1999a) or adiabatic energization of relativistic electrons confined in fossil radio plasma, released by a former active radio galaxy (Enßlin & Gopal-Krishna 2001).

Observationally, the radio halo of A754 appears to be displaced from the main cluster core in the direction of the west relic. This suggests that the halo emission results only from regions that were heated by the reemerging western shock wave after core passage. Since the radiative cooling time of the radio-halo electrons observed at 330 MHz is smaller than 0.3 Gyr, but the shock passage was more than 0.3 Gyr ago (at least in the numerical model), the radio electrons must have been repopulated after the shock passage. In situ, the Fermi II reacceleration (powered by some residual plasma turbulence after the shock passage) of shock-accelerated electrons could be able to reaccelerate the electrons (Brunetti et al. 2001) if the turbulence is able to remain for a few 100 Myr. Alternatively, relativistic protons might be efficiently accelerated at shock waves and would have lifetimes comparable to the cluster age. Since these protons can seed relativistic electrons and positrons into the ICM by hadronic collisions with the ICM ions, they might be responsible for the radio-halo emission that glows for a long time after the shock passage (Dennison 1980; Vestrand 1982; Blasi & Colafrancesco 1999; Dolag & Enßlin 2000). This process would only be efficient in the dense cluster core regions, and thus is likely not important to the formation of peripheral radio relics.

The above scenarios are speculative but make clear predictions, which further observations can confirm. First, further observations can reveal that either or both of the relic structures are real. Second, we expect a high degree of source-intrinsic radio polarization in the east relic because of the nearly perpendicular line of sight to the shock compression direction. The compressed magnetic fields should be roughly aligned with the shock plane and relic major axis, and thus the synchrotron emission should be highly polarized. For the west relic, the geometry is less constrained, but polarization is also very likely.

Further, the steep spectral index of the east relic can be understood, but would likely have different spectral curvature in the two relic formation models. In the Fermi I shock acceleration model, a low Mach number shock would produce a steep power-law radio spectrum (Mach number <3.5 for a spectral index steeper than 1.8). In the revived-fossil radio plasma model, the steep spectrum would be a synchrotron/inverse Compton cooling cutoff that was shifted by the shock compression close to the observed frequency. Additional information on the spectral curvature of the relics might therefore help to discriminate between these two scenarios.

Finally, if radio halos occur only in shocked ICM, as A754 seems to indicate, then one would expect a spatial correlation of shock-heated gas and diffuse synchrotron emission in other clusters that are in the early stages of major merger events. Such a correlation could be observable with high-resolution observations from X-ray satellites such as *Chandra*. At later merger stages, turbulent gas motion, which is stirred by *violently relaxing* dark matter cores, should have erased many of the temperature and radio-halo substructures.

The hypothesis that radio halos occur only in shocked ICM could explain why the postmerger cluster A3667 has no radio halo, despite the fact that two giant cluster radio relics (Röttgering et al. 1997) indicate the presence of peripheral merger shock waves (Enßlin et al. 1998). In this case, the main cluster core seems to be unshocked (Roettiger et al. 1999a; see the temperature map in their Fig. 3) because the merger was likely less violent. There, only a mass ratio of the merging clusters of 5:1 is needed in order to reproduce its X-ray morphology, compared to 2.5:1 for A754 (Roettiger et al. 1998). In the reacceleration scenario (Brunetti et al. 2001), either the shock waves would have injected energetic electrons only into peripheral, low–magnetic-field regions, so that no radio halo occurred, or the necessary reacceleration turbulence would have decayed in the late merger state of A3667 (1 Gyr after core passage). The reacceleration model can be tested because of the high energy cutoff expected in the radio electron spectrum at energies where the cooling timescale is shorter than the acceleration timescale. A stronger halo suppression can be expected in the scenario of radio-halo electrons being produced by shock-accelerated protons. In this scenario, the shock waves in A3667 would have emerged at radii that were too peripheral to host the sufficiently dense thermal proton population required as a target in order for the hadronic secondary electron production to operate efficiently—in addition to the weaker radio emissivities there due to weaker magnetic fields. The hadronic halo scenario will be tested with the next generation of gamma-ray telescopes for the unavoidable gamma radiation from neutral pion decays following hadronic proton-proton collisions (Vestrand 1982; Enßlin et al. 1997; Colafrancesco & Blasi 1998; Blasi 1999; Dolag & Enßlin 2000).

4. CONCLUSIONS

A754 has been successfully imaged at both 330 and 74 MHz. We conclude that these images strongly suggest the existence of both a radio halo and at least one and possibly two radio relics in this galaxy cluster. This finding is especially relevant in light of recent observational and theoretical evidence in favor of a merger-relic connection. Deeper 74 and 330 MHz imaging at higher resolution are clearly warranted to confirm the extended nature of the radio halo and the relic detections. These observations suggest that further study of this system, and similar ones at low frequencies, will open a new window of understanding on cluster dynamics and cluster formation.

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