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ON THE ORIGIN OF RADIO HALOS IN GALAXY CLUSTERS

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ABSTRACT

Previously, it has been recognized that radio halos in galaxy clusters are preferentially associated with merging systems, as indicated by substructure in the X-ray images and temperature maps. Since, however, many clusters without radio halos also possess substructure, the role of mergers in the formation of radio halos has remained unclear. By using power ratios to relate gravitational potential fluctuations to substructure in X-ray images, we provide the first quantitative comparison of the dynamical states of clusters possessing radio halos. A correlation between the 1.4 GHz power ($P_{1.4}$) of the radio halo (or relic) and the magnitude of the dipole power ratio (P_1/P_0) is discovered such that approximately $P_{1.4} \propto P_1/P_0$; i.e., the strongest radio halos appear only in those clusters currently experiencing the largest departures from a virialized state. From the additional consideration of a small number of highly disturbed clusters without radio halos detected at 1.4 GHz and recalling that radio halos are more common in clusters with high X-ray luminosity (Giovannini, Tordi, & Feretti), we argue that radio halos form preferentially in massive ($L_X \gtrsim 0.5 \times 10^{45}$ ergs s^{-1}) clusters experiencing violent mergers ($P_1/P_0 \gtrsim 0.5 \times 10^{-4}$) that have seriously disrupted the cluster core. The association of radio halos with massive, large-P_1/P_0, core-disrupted clusters can account for both the vital role of mergers in accelerating the relativistic particles responsible for the radio emission as well as the rare occurrence of radio halos in cluster samples.

Subject headings: cooling flows — galaxies: formation — galaxies: halos — radio continuum: galaxies — X-rays: galaxies: clusters

1. INTRODUCTION

Diffuse radio emission that cannot be attributed only to individual galaxies in a galaxy cluster is termed a *radio halo* if the emission is centrally located or a *radio relic* if it lies substantially away from the (X-ray) cluster center (for reviews see, e.g., Feretti 2001; Sarazin 2001). Radio halos typically extend to 1 Mpc scales and are characterized by a steep radio spectrum consistent with a synchrotron origin. Until recently radio halos were known to exist in only a handful of galaxy clusters, with Coma being the best-studied example (e.g., Giovannini et al. 1993; Deiss et al. 1997). With the completion of the NRAO VLA Sky Survey (NVSS; Condon et al. 1998) the number of candidate radio halos has risen to approximately 20 (Giovannini, Tordi, & Feretti 1999; Giovannini & Feretti 2000; Liang et al. 2000). However, these radio halos still represent only ∼10% of the cluster populations studied, indicating that they are indeed a rare phenomenon.

Important progress in our understanding of the formation of radio halos has been made recently. First, Govoni et al. (2001) have compared the point-to-point spatial distribution of the radio and X-ray emission in four clusters and have found a linear relationship in two cases and a nearly linear relationship in the other two. The similarity of the radio and X-ray morphologies suggests a direct connection between the thermal X-ray plasma and the nonthermal radio plasma. Second, Colafrancesco (1999) and Liang et al. (2000) have discovered a correlation between radio power $P_{1.4}$ (at 1.4 GHz rest frame) and X-ray temperature T_X such that $P_{1.4}$ increases for larger T_X in their sample of 10 of the most securely detected radio halos. These authors suggest that the $P_{1.4}$-T_X correlation also indicates a direct connection between the radio and X-ray plasmas.

Although there is mounting evidence that the thermal X-ray and nonthermal radio emission are directly related, the source of the relativistic particles giving rise to the nonthermal emission, as well as the question of the rarity of radio halos, remains unexplained. Perhaps the most favored mechanism to accelerate relativistic electrons in clusters is that of mergers (e.g., Tribble 1993), owing to the considerable amount of energy available during a merger (∼10^{64} ergs). The details of this process, however, remain controversial because of the difficulty in directly accelerating the thermal electrons to relativistic energies (e.g., Tribble 1993; Sarazin 2001; Brunetti et al. 2001; Blasi 2001). In fact, owing to this difficulty it is often assumed that a reservoir of relativistic particles is established at some time in the past evolution of the cluster, with the current merger merely serving to reaccelerate relativistic particles from this reservoir. In this case it is unclear whether the current or the past dynamical state of the cluster is the primary factor in the creation of a radio halo.

X-ray observations provide circumstantial evidence for a connection between cluster merging and radio halos (see Feretti 2001 and references therein) because, in particular, radio halos are found only in clusters possessing X-ray substructure and weak (or nonexistent) cooling flows. However, it has been argued (e.g., Giovannini & Feretti 2000; Liang et al. 2000; Feretti 2001) that merging cannot be solely responsible for the formation of radio halos because at least 50% of clusters show evidence for X-ray substructure (Jones & Forman 1999) whereas only ∼10% possess radio halos. (Note that X-ray and optical substructures are well correlated [Kolokotronis et al. 2001].)

Unfortunately, it is difficult to interpret the importance of merging using the observed frequency of substructure since it does not itself quantify the deviation of an individual cluster from a virialized state. In addition, the shocks that could be responsible for particle acceleration will be proportionally stronger in clusters (of the same mass) with the largest departures from a virialized state. To measure the dynamical states of clusters from X-ray images, it is necessary to quantify the cluster morphologies using statistics such as the center shift (Mohr, Fabricant, & Geller 1993; Mohr et al. 1995) and the

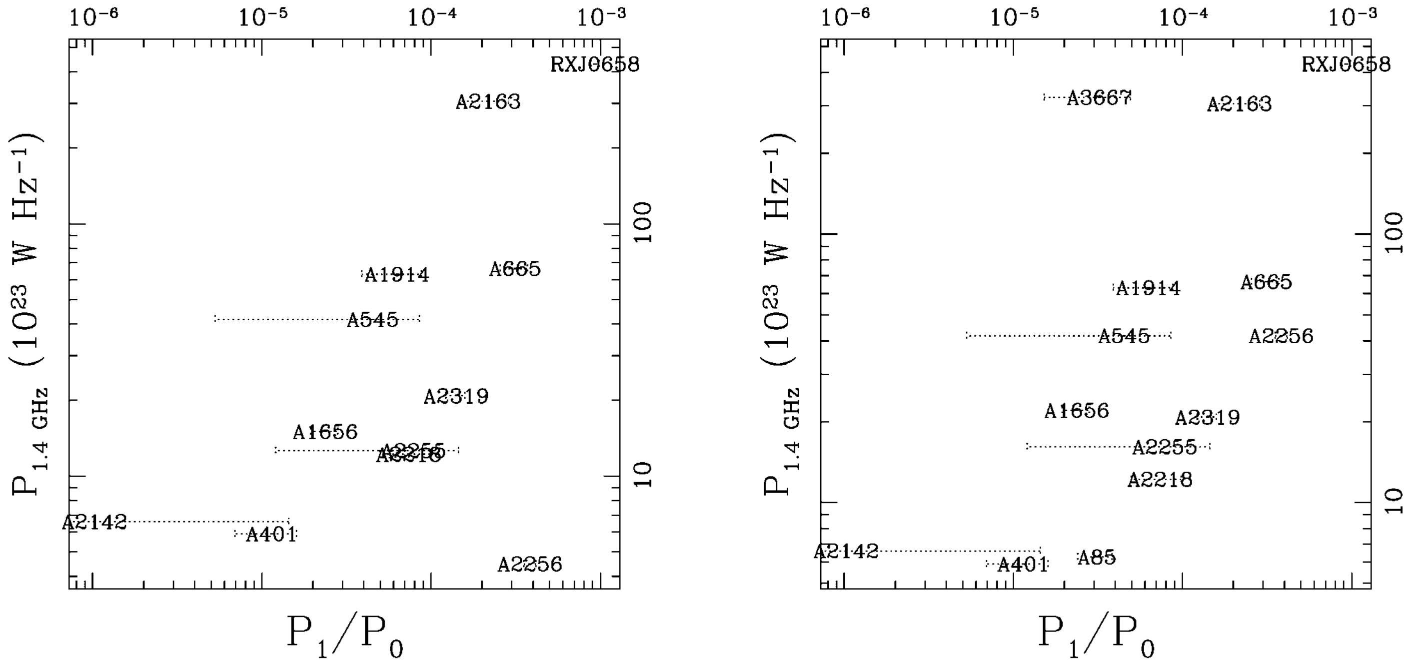

FIG. 1.—Radio power ($P_{1.4}$; 1.4 GHz rest frame) vs. dipole power ratio (P_1/P_0), where $P_{1.4}$ includes emission from (*left*) only radio halos and (*right*) the total diffuse emission from halos and relic sources. The power ratios are computed within a 0.5 Mpc aperture centered on the X-ray emission peak with estimated 1 σ errors shown. (Uncertainties on $P_{1.4}$ are believed to be $\lesssim$10% and are not shown.)

power ratios (Buote & Tsai 1995, 1996, hereafter BT96; Buote 1998).

In this Letter we provide the first quantitative comparison of the dynamical states of clusters possessing detected radio halos. Using the power ratios computed previously from *ROSAT* X-ray images, we find a correlation between the power of the radio halo and the magnitude of the dipole power ratios; i.e., the strongest radio halos appear only in those clusters currently experiencing the largest departures from a virialized state. We argue that this correlation confirms the vital role of mergers in accelerating the relativistic particles responsible for the radio emission and also explains the rarity of radio halos.

2. RADIO POWER AND CLUSTER DYNAMICAL STATES

We compiled a sample of 14 clusters selected primarily from the catalogs of radio halos and relics of Feretti (2001), Giovannini et al. (1999), and Giovannini & Feretti (2000) that also have power ratios measured by BT96. (Note that the radio powers estimated from the NVSS may be underestimated because of the high noise level [e.g., Giovannini et al. 1999].) Also included is the cluster RX J0658−5557 (1E 0657−56), which has been reported to possess the most powerful radio halo to date (Liang et al. 2000) even though it was not analyzed by BT96. We obtained a deep HRI exposure (58 ks) of RX J0658 from the *ROSAT* public data archive and computed power ratios in a manner similar to that described by BT96.

It can be shown that the power ratios are a direct measure of the dynamical state of a cluster modulo projection effects (Buote 1998). Briefly, each P_m represents the square of the mth multipole of the two-dimensional pseudopotential generated by the X-ray surface brightness evaluated over a circular aperture. The aperture is positioned at the peak of the X-ray image to compute the dipole power ratio, P_1/P_0, but is located at the center of mass (surface brightness) to compute the higher order moments (see BT96). Large departures from a virialized state are then indicated by large power ratios for the lowest order multipoles since they contribute most to the potential.

In Figure 1 we plot radio power versus P_1/P_0 evaluated over a 0.5 Mpc aperture radius. (We assume $H_0 = 80$ km s^{-1} Mpc^{-1} and $q_0 = 0$ following BT96.) Although the sample is small, a clear trend is observed: radio power tends to increase with increasing P_1/P_0, or the magnitude of the deviation from a virialized state, such that approximately $P_{1.4} \propto P_1/P_0$. Moreover, all radio halo clusters except A2142 have $P_1/P_0 \gtrsim 10^{-5}$, whereas essentially all massive cooling-flow clusters populate $P_1/P_0 \lesssim 10^{-5}$ (see BT96). Since most of the radio halos in Figure 1 have P_1/P_0 values indicative of unrelaxed systems, this confirms previous circumstantial evidence that radio halos preferentially exist in merging systems without massive cooling flows (e.g., Feretti 2001).

When we consider only the emission from radio halos, the cluster A2256 appears to be an outlier; i.e., it possesses a large value of P_1/P_0 for a weak radio halo. However, when the emission from both radio halos and relics is considered, A2256 fits in much better (Fig. 1, *right panel*). Another cluster, A85, that possesses only a radio relic also supports the trend of larger $P_{1.4}$ for larger P_1/P_0 for both halos and relics.

The relic-only cluster A3667 appears to be a genuine outlier in that it has a relatively small value of P_1/P_0 for its large radio power. In principle this deviation could be attributed to a projection effect (i.e., smearing of substructure). However, the relic source of A3667 is offset ∼1 Mpc from the X-ray center, and P_1/P_0 is twice as large in the 1 Mpc aperture, indicating a substantial large-scale dynamical disturbance. In fact, the general $P_{1.4}$-P_1/P_0 trend discussed above applies also when P_1/P_0 is computed within a 1 Mpc aperture, but in this case A3667 has a large value of P_1/P_0 similar to (for example) A2163, consistent with the trend. Consequently, the "anomalous" position of A3667 can be attributed to P_1/P_0 computed within the 0.5 Mpc aperture not being a sensitive enough indicator of the dynamical disturbance associated with the relic on ∼1 Mpc scales. An appropriately weighted average of P_1/P_0 over an entire cluster is probably required to obtain a fully consistent representation of halos and relics in the $P_{1.4}$-P_1/P_0 plane.

We mention that for the power ratios computed within apertures located at the center of mass (surface brightness), only the odd power ratio, P_3/P_0, clearly displays a trend similar to P_1/P_0. However, the statistical uncertainties for this higher order moment are large, and the correlation is observed only for systems having $P_{1.4} > 10^{24}$ W Hz^{-1}. The even power ratios (e.g., P_2/P_0) do not show a correlation with $P_{1.4}$. Apparently only dynamical disturbances that contribute primarily to the odd power ratios correlate with the power of radio halos and relics.

3. DISCUSSION

3.1. *Radio Halo and Relic Formation*

Previously it has been recognized that radio halos and relics tend to be associated with mergers; however, since a higher percentage of clusters without radio halos show evidence for substructure, the importance of merging in the formation of radio halos has remained unclear (e.g., Feretti 2001). The $P_{1.4}$-P_1/P_0 correlation (Fig. 1) not only confirms previous circumstantial evidence relating the presence of radio halos to mergers but, more importantly, establishes for the first time a quantitative relationship between the "strength" of radio halos and relics ($P_{1.4}$) and the "strength" of mergers (P_1/P_0). Moreover, in the $P_{1.4}$-P_1/P_0 plane both radio halos and relics may be described consistently, which provides new evidence that both halos and relics are formed via mergers. The $P_{1.4}$-P_1/P_0 correlation supports the idea that shocks in the X-ray gas generated by mergers of subclusters accelerate (or reaccelerate) the relativistic particles responsible for the radio emission.

3.2. *Implications of Outliers*

Most of the clusters studied by BT96 do not possess radio halos or relics. If we consider the brightest ∼30 clusters for which the sample of BT96 is more than 50% complete (X-ray–selected), most of the clusters without radio halos or relics have $P_1/P_0 \lesssim 10^{-5}$, placing them in the lower left portion of Figure 1. These clusters are therefore approximately relaxed systems and, in accordance with the formation scenario discussed previously, do not have powerful radio halos or relics.

However, three bright clusters (A754, A3266, Cygnus A) exist that are highly morphologically disturbed ($P_1/P_0 \geq 10^{-4}$) yet have no (or only weakly) detected emission from a radio halo at 1.4 GHz. Thus, each would lie in the bottom right portion of Figure 1 as significant outliers in the $P_{1.4}$-P_1/P_0 correlation. It is possible that powerful radio halos for these systems have not been detected at 1.4 GHz owing to their steep spectra; e.g., after our Letter was submitted we became aware of a paper by Kassim et al. (2001) that presents evidence for a very powerful radio halo in A754 at 330 MHz. Whether halos in these or other clusters are detected at other radio frequencies is an important subject for future studies. For the remainder of this Letter we confine our discussion to studies at 1.4 GHz.

These clusters do have strong radio emission either from a central source (Cygnus A) or collectively from several point sources (A754 and A3266) that could be related to their current dynamical states. These clusters have similar structure in their X-ray temperature distributions where relatively cool gas exists within the central few hundred kiloparsecs, and hotter gas, consistent with shock heating, is located at larger radii (e.g., Henry & Briel 1995; Henriksen & Markevitch 1996; Markevitch, Sarazin, & Vikhlinin 1999; Markevitch et al. 2001; Henriksen et al. 2000; Sarazin 2001). The temperature maps of these systems imply mergers that have not disrupted the cores, and detailed hydrodynamical models confirm that the mergers in these systems are off-axis and must be in the very earliest stages (e.g., Roettiger, Stone, & Mushotzky 1998; Flores, Quintana, & Way 2000; Roettiger & Flores 2000).

The temperature structure of these deviant clusters is similar to that of A3667 (e.g., Vikhlinin, Markevitch, & Murray 2001), which also has no detected radio halo. As discussed previously, this system has a large-scale dynamical disturbance with a large value of $P_1/P_0 \approx 10^{-4}$ within the 1 Mpc aperture similar to those clusters with the most powerful halos. In contrast, A2256, the most deviant cluster in Figure 1 when we consider only the emission from radio halos, does have a measured weak radio halo. Unlike the other clusters described in this section, the X-ray temperature map of A2256 (e.g., Sun et al. 2001) indicates a more advanced merger that has begun to disrupt the core.

The properties of these deviant clusters suggest that radio halos form only when a sufficiently large dynamical disturbance has proceeded fully into the core of a cluster. The formation of halos and relics also appears to be related since the relic sources (most notably A2256) are consistent with the $P_{1.4} \propto P_1/P_0$ trend when both halo and relic emission are included. Further study is needed to establish the existence of a direct link between halos and relics, especially to ascertain whether peripheral relics are formed preferentially at early times during mergers.

Finally, the faintest cluster studied by BT96, A514, has the largest power ratios but does not possess a radio halo. This cluster consists of several small clumps embedded in a diffuse halo of X-ray emission (e.g., Fig. 5 in Buote & Tsai 1995). The lack of a radio halo could arise because A514 is apparently in the earliest formation stages and perhaps has not had enough time to generate a reservoir of relativistic particles for reacceleration. Alternatively, the low mass of this cluster may indicate that insufficient energy is available to accelerate particles to the speeds required for synchrotron emission.

3.3. *The Importance of the Mass of the Cluster*

Although $P_{1.4} \propto P_1/P_0$ (Fig. 1) holds approximately for systems with radio halos (and no relics), there is considerable scatter for a given value of P_1/P_0. For example, A665 and A2163 have similar values of P_1/P_0 but differ by a factor of ≈5 in radio power. It is possible that projection effects account for the similar values of P_1/P_0 for A665 and A2163, which will become apparent as the sample of radio halos with computed values of P_1/P_0 increases; or perhaps the dynamical states of these clusters could be distinguished by using a radially averaged value of P_1/P_0 (§ 2). However, this large difference in radio power could imply the existence of another physical parameter fundamental to the formation of radio halos.

The mass of the cluster is a logical candidate for a fundamental parameter since the energy available to accelerate relativistic particles during a merger scales as $\sim M^2$. The positive correlations of $P_{1.4}$ with L_X and T_X discovered by Giovannini et al. (1999), Colafrancesco (1999), and Liang et al. (2000) provide strong evidence for the influence of the cluster mass on the power of radio halos. This mass dependence would explain the lack of a radio halo in the highly disturbed low-luminosity cluster A514 discussed above.

It is possible that the scatter noted above for the relation

$P_{1.4} \propto P_1/P_0$ could be reduced if cluster masses are considered. For example, if $M \sim T_X^{3/2}$ as appropriate for pure gravitational infall, then using the temperatures of White (2000) we obtain values of $(P_1/P_0)T_X^{3/2}$ of 7.1×10^{-4} for A665 and 10.5×10^{-4} for A2163; i.e., the cluster with larger $P_{1.4}$ now also has larger $(P_1/P_0)T_X^{3/2}$. Observations of a large sample of clusters will be required to determine whether the mass, the projection effects, the method of computing P_1/P_0, or the frequency used to evaluate the radio power can reduce the scatter in Figure 1.

3.4. *Rarity of Radio Halos and Relics*

The infrequent occurrence of radio halos in X-ray cluster samples can be understood when both the dynamical state and the mass of the cluster are considered. In their study of an X-ray flux-limited sample of 205 clusters, Giovannini et al. (1999) only detect radio halos in less than 5% of clusters with $L_X < 0.5 \times 10^{45}$ ergs s^{-1} but in ≈30% of clusters with $L_X > 1.0 \times 10^{45}$ ergs s^{-1} ($H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$). Hence, the need for sufficient L_X, therefore mass, can explain the rarity of radio halos in lower mass clusters.

For the most massive and X-ray luminous systems, the relative frequency (<50%) of radio halos cannot be explained by considering only the mass or, equivalently, only the X-ray temperature. For example, both A665 and A2029 have $T_X \approx 8$ keV (e.g., White 2000), but only A665 has a powerful radio halo. However, A665 is currently experiencing a violent merger (large P_1/P_0) whereas A2029 is apparently a nearly relaxed system (small P_1/P_0). In fact, of the brightest ∼30 clusters in the sample of BT96, virtually all clusters with $P_1/P_0 > 0.5 \times 10^{-4}$ either possess radio halos (relics) or suggest an early merger that has not fully disrupted the cluster core (see § 3.2). One can select just for the radio halos by eliminating clusters that demonstrate characteristic X-ray temperature structure (see § 3.2) and perhaps also those with an increasing P_1/P_0 radial profile (e.g., the outliers A3266 and Cygnus A; see BT96).

Thus, for massive clusters, the occurrence of radio halos may be explained by the frequency of clusters currently experiencing violent, core-disrupting mergers. On average, P_1/P_0 is expected to increase with increasing redshift owing to the higher incidence of merging (Buote 1998), which would lead to a higher incidence of radio halos. However, on average, cluster masses are lower at earlier times, implying a lower incidence of radio halos. Each of these factors is dependent on the assumed cosmology, and future theoretical work is therefore required to establish whether the abundance of radio halos (1) increases or decreases with redshift and (2) provides an interesting test of cosmological models.

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