ABSTRACT

Clusters of galaxies are sites of acceleration of charged particles and sources of nonthermal radiation. We report on new constraints on the population of cosmic rays in the intracluster medium (ICM) obtained via radio observations of a fairly large sample of massive, X-ray–luminous galaxy clusters in the redshift interval 0.2–0.4. The bulk of the observed galaxy clusters does not show any hint of megaparsec-scale synchrotron radio emission at the cluster center (radio halo). We obtained solid upper limits to the diffuse radio emission and discuss their implications for the models for the origin of radio halos. Our measurements allow us to also derive a limit to the content of cosmic-ray protons in the ICM. Assuming spectral indices of these protons δ = 2.1–2.4 and μG level magnetic fields, as from rotation measures, these limits are 1 order of magnitude deeper than present EGRET upper limits, while they are less stringent for steeper spectra and lower magnetic fields.

Subject headings: acceleration of particles — galaxies: clusters: general — radiation mechanisms: nonthermal — radio continuum: general — X-rays: general

Online material: color figure

1. INTRODUCTION

Clusters of galaxies are ideal astrophysical environments for particle acceleration. Large-scale shocks that form during the process of cluster formation are believed to be efficient particle accelerators (e.g., Sarazin 1999; Gabici & Blasi 2003; Ryu et al. 2003; Ptormmer et al. 2006). Cosmic rays (CRs) can also be injected into the ICM from ordinary galaxies and AGNs (e.g., Völk & Atouyan 1999), and turbulent eddies may contribute to the particle acceleration process (e.g., Brunetti & Lazarian 2007). CRs accelerated within the cluster volume would then be confined for cosmological times, and the bulk of their energy is expected in protons since they have radiative and collisional lifetimes much longer than those of the electrons (e.g., Blasi et al. 2007 for a review).

While present gamma-ray observations can only provide upper limits to the average energy density of CR protons in the ICM (e.g., Reimer 2004), the presence of relativistic electrons in a number of clusters has been ascertained via the detection of a tenuous synchrotron radio emission: giant radio halos (RHs) and mini-radio halos, fairly symmetric sources at the cluster center, and radio relics, elongated sources at the cluster periphery (e.g., Feretti & Giovannini 2007). It is customary to classify the models for the origin of RHs in “secondary electron” (e.g., Blasi & Colafrancesco 1999) and “reacceleration” models (e.g., Brunetti et al. 2001; Petrostian 2001), depending on whether the radiating electrons are produced as secondary products of hadronic interactions or reaccelerated by turbulence from a preexisting population of nonthermal seeds in the ICM, respectively. These models predict a different connection between radio and X-ray properties of clusters, which are discussed in this Letter and compared with new observations. In § 2 we review the expectations of the different models, in § 3 we briefly present the radio observations of our cluster sample, and in §§ 4 and 5 we report and discuss our results. Concordance (H₀ = 70, Ωₚ = 0.3, Ωₐ = 0.7) cosmology is used.

2. RADIO–X-RAY CORRELATION AND ORIGIN OF RHs

Giant RHs follow a correlation between their radio power at 1.4 GHz (P₁₄) and physical size, and the X-ray luminosity (Lₓ) and temperature of clusters in which they are found (e.g., Liang et al. 2000; Bacchi et al. 2003; Cassano et al. 2006, 2007).

In this Letter we focus on the P₁₄–Lₓ correlation that relates directly observable quantities. The bulk of giant RHs has been discovered from the analysis of relatively shallow surveys (NVSS, Giovannini et al. 1999, hereafter G99; WENSS, Kempner & Sarazin 2001, hereafter KS01), and a relevant issue is how observational biases may affect this correlation. There is agreement on the fact that the upper envelope of the P₁₄–Lₓ correlation is likely to be solid (e.g., Clarke 2005), but the effect of observational biases on the lower envelope is more problematic (Rudnick et al. 2006). Indeed, if all clusters would have cluster-scale radio emission at the level of presently known RHs, then the P₁₄–Lₓ trend may possess a fairly large spread, with lower luminosity RHs falling just below present observational limits. On the other hand, it is also possible that clusters have a physical bimodal distribution, with the RH clusters following the correlation and with other clusters having no (or much weaker) cluster-scale radio emission.

The first possibility is essentially what secondary models would expect (e.g., Miniati et al. 2001; Dolag & Ensslin 2000). This comes from the combination of two points: the magnetization at μG level is believed to be a very common property of the ICM (Clarke et al. 2001; Govoni & Feretti 2004), and CR protons accumulated in galaxy clusters for cosmological timescales provide a fairly stable continuous source of injection of secondary electrons and positrons in the ICM.

On the other hand, an unavoidable prediction of the reacceleration scenario is a bimodality of clusters. In this scenario particles are supposed to be reaccelerated by MHD turbulence in the ICM, and this requires enough turbulence to boost electrons at the energies necessary to emit synchrotron radiation at GHz frequencies. Thus, giant RHs should be strictly connected to massive and merging systems, where indeed enough...
turbulence can be developed (Cassano & Brunetti 2005), and should live for relatively short timescales (1 Gyr or less) because of the finite dissipation timescale of turbulence. In this scenario merging clusters are expected to move with time from a “radio-quiet” region in the $P_{1.4}$-$L_X$ plane to the $P_{1.4}$-$L_X$ correlation. This happens in a relatively short timescale, of the order of $\approx 10^8$ yr (i.e., the acceleration timescale of the emitting particles; see Brunetti et al. 2004, Fig. 19), and thus the region between RHs and radio-quiet clusters in the $P_{1.4}$-$L_X$ plane should be poorly populated. Thus, the distribution of clusters in the $P_{1.4}$-$L_X$ plane is important to constrain current models.

3. CLUSTER SAMPLE AND GMRT OBSERVATIONS

From the ROSAT-ESO Flux Limited X-ray (REFLEX) galaxy cluster catalog (Böhringer et al. 2004) and from the extended ROSAT Brightest Cluster Sample (eBCS) catalog (Ebeling et al. 1998, 2000) we selected all clusters with $0.2 \leq z \leq 0.4$, $L_X(0.1-2.4$ keV) $> 5 \times 10^{44}$ ergs s$^{-1}$, and with declination $\delta \geq -30^\circ$ (for the REFLEX) and $15^\circ < \delta < 60^\circ$ (for the eBCS). These selection criteria led to a sample of 50 X-ray-selected galaxy clusters (27 from REFLEX, 23 from eBCS) with similar luminosity. The sample includes six clusters with well-studied RHs (A2744, A1300, A2163, A2773, A2219, A2390; e.g., Feretti & Giovannini 2007; Bacchi et al. 2003) and A1758 for which hint of diffuse emission is also reported (G99; KS01).

We carried out GMRT (Giant Metrewave Radio Telescope) observations at 610 MHz only for 34 clusters in the sample (those with no high-sensitivity radio information already available, and not included in the GMRT cluster key project); each cluster was observed for 2–3 hr (hour angle 3–5). Thanks to the distribution of antennas at GMRT, we obtained images for each cluster with resolutions ranging from $6''$ to $25''$ and rms (1 $\sigma$) $\approx 30–180$ $\mu$Jy beam$^{-1}$ (Venturi et al. 2007, hereafter V07; T. Venturi et al., in preparation), which allows us to image both compact and extended sources in the fields. We detected RHs in four of them (RXCJ 2003, A209 and RXCJ 1314–2515, V07; A697 T. Venturi et al., in preparation); a relic was also found in A521, Giacintucci et al. 2006). No hint of cluster-scale radio emission was found in the remaining 29 clusters. For these clusters it is necessary to place solid upper limits to the flux density of their Mpc scale radio emission (few arcminutes at the redshifts of our clusters). In Figure 1 we report the normalized integrated brightness profiles of well-studied RHs: they are quite similar and $\approx 50\%$ of the luminosity, $L_{\nu,5}$, is emitted within about half radius, $R_{\nu,5}$. A detection limit based on the brightness within $R_{\nu,2}$ gives a 610 MHz luminosity in W Hz$^{-1}$ ($\theta_\circ$ is the beam FWHM),

$$L_\nu \geq 3.5 \times 10^{21} \left(1 + \frac{z}{0.25}\right)^4 \left(\frac{\text{rms}}{50 \mu \text{Jy beam}^{-1}}\right) \left(\frac{25''}{\theta_\circ}\right) \left(\frac{R_\nu}{0.5 \text{ Mpc}}\right)^2,$$

which is $\approx 50$ times smaller than luminosities of known giant RHs at $z \approx 0.25$ (V07).

In order to derive more solid constraints to use in this Letter, we inject fake RHs in our data sets. We model the brightness profile in Figure 1 with sets of optically thin spheres with different radius and flux densities, and obtain “families” of fake RHs with total flux densities $S_{\text{RH}}$ ranging from 3 to 300 mJy and angular diameters from 180$''$ to 350$''$. Those fake RHs were injected into the uv components of our cluster data sets by means of the task UVMOD in AIPS, and the resulting data sets were imaged with the procedures given in V07 with the task IMAGR at resolutions in the range 10$''$–25$''$. The injected flux density of RHs is not fully recovered by the imaging, and an increasing fraction of injected flux is lost when $S_{\text{RH}}$ decreases, and/or the total angular size increases; an example is given in Figure 2. We also found very little dependence on the resolution of the image, at least in the range 15$''$–25$''$. We find that the lowest value of the injected flux density that leaves a residual flux in the images that can be reasonably interpreted as due to an extended low brightness radio source on the basis of the standard radio imaging is in the range $\approx 5–12$ mJy. This marks the value of the upper limit to the injected flux of RHs and scales both with the largest angular size of the fake RHs and with the rms of the final image (e.g., Fig. 3). Note, however, that at this point a residual flux is still formally detected at $4–5 \sigma$ level on an area of a few beams in the low-resolution images (e.g., Fig. 2). Our limits should thus be considered conservative; they are typically $\approx 2.5$ times larger than those in equation (1).

We derive these solid limits to the detection of RHs for 20 clusters observed at the GMRT. Indeed, among the observed 29 clusters with no hint of cluster-scale emission, we excluded A3444, A1682, and Z7160, where extended radio galaxies in the field make it difficult to straightforwardly apply our procedure, and we also excluded six clusters in our sample with poor quality of the data ($\text{rms} > 120 \mu \text{Jy beam}^{-1}$ caused by interferences).

4. RESULTS

In Figure 4 we report the distribution of clusters in the $P_{1.4}$-$L_X$ plane. Giant RHs and upper limits obtained from UVMOD simulations (§ 3) with $R_\nu = 0.5$ Mpc are reported in magenta. These solid upper limits lie about 1 order of magnitude below the correlation for giant RHs. This allows us to firmly establish that the $P_{1.4}$-$L_X$ correlation (Cassano et al. 2006, Fig. 4, solid line) is real and that its lower envelope is not driven by observational biases (at least for $L_X \geq 5 \times 10^{44}$ ergs s$^{-1}$, i.e., the selection limit of our clusters).

Most importantly, we find that clusters with similar $L_X$ and redshift have a clear bimodal distribution. Cluster-scale radio
emission at the level of presently studied RHs is not ubiquitous in galaxy clusters, and only \( \approx \frac{1}{4} \) of clusters in our sample host a RH. Although no homogeneous high-resolution X-ray data are still available for all our clusters, the RHs are found in dynamically disturbed systems, while clusters without RHs are either disturbed or relaxed systems (V07). Figure 4 (green arrows) shows that even more stringent upper limits are obtained considering radio emission on cluster-core scale \( (R_h = 0.25 \text{ Mpc}) \).

It is challenging for secondary models to accommodate the observational picture of Figure 4. These models would expect the cluster-scale radio emission to be more common and predict some general \( P_{1.4}-L_x \) trend for all clusters with some scattering due to the effect of the different CR proton content and magnetic field among clusters (e.g., Miniati et al. 2001; Dolag 2006). Thus, strong dissipation of the magnetic field in the ICM in relatively short timescales is necessary to reconcile secondary model expectations with the data, although reconciling this dissipation with present theoretical understanding (e.g., Subramanian et al. 2006) and data (e.g., Govoni & Feretti 2004) might be problematic. Recently, Pfrommer (2007) presented numerical simulations of secondary and shock-accelerated particles. Also, in this case extended synchrotron emission, at least on a cluster-core scale, is predicted to be common, at the level of presently known RHs, and clusters are predicted to follow relatively well-defined correlations (Pfrommer 2007, Fig. 1) with merging and nonmerging systems lying on the upper and lower envelope of correlations, respectively. Thus, similar considerations can also be applied to this scenario.

5. LIMITS ON CRs IN NON–RADIO-EMITTING CLUSTERS

Gamma-ray observations of a number of nearby galaxy clusters limit the energy density of CR protons in these clusters to 10%–20% of the thermal energy (Pfrommer & Ensslin 2004; Reimer 2004). The upper limits for clusters with no RHs of

![Fig. 2.—Example of injection of fake RHs with apparent radius \( \Theta_h = 150'' \) and \( S_{\text{BH}} = 0, 8, 11, \) and 15 mJy (from left to right). The rms of the image is 65 \( \mu \text{Jy beam}^{-1} \) \( \Theta_h = 20' \times 24'' \). Contour levels are given for 0.1 \( \times \) (1, 2, 4, 8, 16, 32, 64) mJy beam\(^{-1} \). In this case diffuse emission is revealed with standard analysis (including comparison between high- and low-resolution images) for \( S_{\text{BH}} > 11 \text{ mJy} \).

![Fig. 3.—Upper limits on the detectable RH flux (arrows) from UVMOD simulations (GMRT cluster field with rms = 80 \( \mu \text{Jy beam}^{-1} \) and beam = \( 20' \times 22'' \)) as a function of apparent radius \( \Theta_h \) (in arcseconds). The solid line marks the constant brightness scaling, and the dashed line marks the \( 1/\Theta_h \) scaling. The vertical dotted lines mark the range of \( \Theta_h \) spanned by our clusters \( (R_h = 0.5 \text{ Mpc}) \).

![Fig. 4.—Clusters in the \( P_{1.4}-L_x \) diagram: published giant RHs in our sample (magenta filled circles), other giant RHs at \( z > 0.2 \) (magenta open circles), and at \( z < 0.2 \) (magenta filled squares). Upper limits are obtained assuming \( R_h = 0.5 \text{ (magenta arrows) and 0.25 Mpc (green arrows) and are scaled at 1.4 GHz with a typical spectral index of RHs, } \alpha = 1.3 \) [Feretti et al. 2004; \( P(\nu) \propto \nu^{-\alpha} \). The mini-halo A2390 and the small RH RXJ1314 that are in our sample are also reported (green asterisks). RHs taken from GMRT observations are 1 = A209, 2 = RXJ2003, and 3 = RXJ1314 (TV07). Estimated dispersions in \( P_{1.4} \) at fixed cluster mass/temperature from simulations of secondary models are reported (from left to right: Miniati et al. 2001; Dolag & Ensslin 2000; Pfrommer 2007).
our sample allow us to obtain indirect upper limits to the energy density of CR protons in these clusters. Indeed, by requiring that radio emission from secondary $e^\pm$ is below the upper limits in Figure 4, one gets constraints on the content of CR protons from which secondaries are injected.

We use the formalism in Brunetti & Blasi (2005) to calculate the stationary spectrum of secondary pairs in the ICM. Typical constraints to the CRs content are given in Figure 5 by simply assuming the bimodal distribution in the $P_{\gamma}-L_X$ plane (Fig. 4); this is in line with the expectation of the reacceleration scenario. On the other hand, in order to reconcile these observations with expectations from secondary models, strong dissipation of the magnetic field in the clusters with no radio emission is necessary.

Our measurements allow us to also derive simple limits on the presence of CR protons in the ICM (Fig. 5). In the case of the relatively flat spectral energy distribution of these CRs stringent upper limits can be obtained: the energy density of CRs should be $\leq 1\%$ of the thermal energy in case of $\gtrsim 0.1$ G field strength. This would make problematic the detection of gamma rays from $\pi^0$ decay in clusters with GLAST. On the other hand, by assuming steeper spectral energy distributions of these CRs (or lower magnetic fields), our limits become less stringent.

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6. CONCLUSIONS

We have reported on constraints on the origin of RHs and on the CR content in the ICM obtained via radio observations of a fairly large sample of X-ray luminous clusters at $z=0.2–0.4$. In the bulk of these clusters we do not find evidence of $M_{\text{pc}}$-scale radio emission at the level of RHs. Our conclusions become even more stringent considering radio emission on cluster-core scale, typical of smaller RHs and mini-halos.

We firmly confirm that RH clusters follow a “physical” correlation between synchrotron and X-ray luminosities. We find that clusters have a bimodal distribution in the $P_{\gamma}-L_X$ plane (Fig. 4); this is in line with the expectation of the reacceleration scenario. On the other hand, in order to reconcile these observations with expectations from secondary models, strong dissipation of the magnetic field in the clusters with no radio emission is necessary.

We have reported on constraints on the origin of RHs and on the CR content in the ICM obtained via radio observations of a fairly large sample of X-ray luminous clusters at $z=0.2–0.4$. In the bulk of these clusters we do not find evidence of $M_{\text{pc}}$-scale radio emission at the level of RHs. Our conclusions become even more stringent considering radio emission on cluster-core scale, typical of smaller RHs and mini-halos. In the case of the relatively flat spectral energy distribution of these CRs stringent upper limits can be obtained: the energy density of CRs should be $\leq 1\%$ of the thermal energy in case of $\gtrsim 0.1$ G field strength. This would make problematic the detection of gamma rays from $\pi^0$ decay in clusters with GLAST. On the other hand, by assuming steeper spectral energy distributions of these CRs (or lower magnetic fields), our limits become less stringent.

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