EVIOLVATION AND DISTRIBUTION OF MAGNETIC FIELDS FROM ACTIVE GALACTIC NUCLEI IN GALAXY CLUSTERS. II. THE EFFECTS OF CLUSTER SIZE AND DYNAMICAL STATE

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ABSTRACT

Theory and simulations suggest that magnetic fields from radio jets and lobes powered by their central supermassive black holes can be an important source of magnetic fields in the galaxy clusters. This is Paper II in a series of studies where we present self-consistent high-resolution adaptive mesh refinement cosmological magnetohydrodynamic simulations that simultaneously follow the formation of a galaxy cluster and evolution of magnetic fields ejected by an active galactic nucleus. We studied different galaxy clusters with virial masses ranging from $1 \times 10^{14}$ to $2 \times 10^{15} M_\odot$. In this work, we examine the effects of the mass and merger history on the final magnetic properties. We find that the evolution of magnetic fields is qualitatively similar to those of previous studies. In most clusters, the injected magnetic fields can be transported throughout the cluster and be further amplified by the intracluster medium (ICM) turbulence during the cluster formation process with hierarchical mergers, while the amplification history and the magnetic field distribution depend on the cluster formation and magnetism history. This can be very different for different clusters. The total magnetic energies in these clusters are between $4 \times 10^{57}$ and $10^{61}$ erg, which is mainly decided by the cluster mass, scaling approximately with the square of the total mass. Dynamically older relaxed clusters usually have more magnetic fields in their ICM. The dynamically very young clusters may be magnetized weakly since there is not enough time for magnetic fields to be amplified.

\textbf{Key words:} galaxies: active – galaxies: clusters: general – magnetic fields – magnetohydrodynamics (MHD) – methods: numerical

\textbf{Online-only material:} color figures

1. INTRODUCTION

The increasing detections of radio emission from galaxy clusters, called radio halos and relics (see Carilli & Taylor 2002; Ferrari et al. 2008; Giovannini et al. 2009), suggest that the intracluster medium (ICM) is permeated with magnetic fields. Radio halos are generally diffuse and extended over $\gtrsim 1$ Mpc, covering the whole clusters, while radio relics, which are often observed at the edges at clusters, can extend as long as 2 Mpc (e.g., van Weeren et al. 2010). By assuming that the total energy in relativistic electrons is comparable to the magnetic energy, the magnetic fields in the cluster halos can be estimated at $0.1–1.0 \mu G$ and the total magnetic energy can be as high as $10^{51}$ erg (Feretti 1999).

Magnetic fields in galaxy clusters are also extensively studied through Faraday rotation measurements (FRMs). Distribution of FRMs, combined with the ICM density measurement, often yields cluster magnetic fields of a few to $10 \mu G$ level, mostly in the cluster centers (Carilli & Taylor 2002). More interestingly, FRM was investigated to suggest that cluster magnetic fields may have a Kolmogorov-like turbulent spectrum in core regions (Vogt & Enßlin 2005), with an energy spectrum peak at several kpc. Other studies (e.g., Taylor & Perley 1993; Eilek & Owen 2002) have suggested that the coherence scales of magnetic fields can range from a few kpc to a few hundred kpc, implying large amounts of magnetic energy and fluxes in the ICM (Colgate & Li 2000). Recently, study of magnetic fields by FRM (Govoni et al. 2006; Guidetti et al. 2008; Bonafede et al. 2010) are extended to the outer part of clusters by observations of more radio galaxies behind or embedded in these clusters. It is expected that the Extended Very Large Array will provide unprecedented new observations on the magnetic fields in the ICM.

It is unlikely that magnetic fields have been dynamically important during the cluster formation. But it is suggested that the strength and geometry of magnetic fields in clusters may play a crucial role in cluster formation through other processes, such as heat transport, which consequently affect the applicability of clusters as sensitive probes for cosmological parameters (Voit 2005). In addition, since magnetic fields are closely related to synchrotron emission and FRM, the distribution of magnetic fields is important to the understanding the radio observations of the ICM.

Magnetic field evolution is highly nonlinear during cluster formation and difficult to study analytically. Cosmological magnetohydrodynamic (MHD) simulations are being used to study the properties of magnetic fields in the ICM. Such simulations can be very useful in interpreting the magnetic field information from the observation results. Since the origin of cluster magnetic fields is still being debated (Widrow 2002), various initial magnetic fields are used in MHD cluster formation simulations. Simulations were done with initial magnetic fields either from some random or uniform fields at high redshifts (Dolag et al. 2002; Dubois & Teyssier 2008; Dubois et al. 2009) or from the outflows of normal galaxies (Donnert et al. 2009). All these simulations have found that fields can be further amplified by cluster merger (Roettiger et al. 1999) and turbulence in addition to collapse and their findings roughly...
The Astrophysical Journal, 739:77 (16pp), 2011 October 1

Xu et al.

Table 1
Properties of Simulated Galaxy Clusters

| Name | r_{200}(Mpc) | M_{200}(M_{\odot}) | M_{\text{gas}}(M_{\odot}) | Cluster Properties ($z = 3$) |
|------|--------------|--------------------|---------------------------|-----------------------------|
| R1   | 2.161        | 1.252e15           | 1.863e14                  | 0.194                       |
| R2   | 1.909        | 8.633e14           | 1.215e14                  | 0.171                       |
| R3   | 1.590        | 4.985e14           | 7.116e13                  | 0.160                       |
| R4   | 1.364        | 3.149e14           | 5.000e13                  | 0.191                       |
| R5   | 1.148        | 1.877e14           | 2.864e13                  | 0.190                       |
| R6   | 0.927        | 9.897e13           | 1.491e13                  | 0.171                       |
| U1a  | 2.498        | 1.934e15           | 2.661e14                  | 0.191                       |
| U1b  | 2.468        | 1.866e15           | 2.733e14                  | 0.143                       |
| U2a  | 1.743        | 6.572e14           | 8.697e13                  | 0.089                       |
| U2b  | 1.718        | 6.292e14           | 7.963e13                  | 0.142                       |
| U3   | 1.709        | 6.198e14           | 8.105e13                  | 0.116                       |
| U4   | 1.675        | 5.829e14           | 7.665e13                  | 0.126                       |
| U5   | 1.626        | 5.338e14           | 7.370e13                  | 0.133                       |
| U6   | 1.447        | 3.763e14           | 5.312e13                  | 0.146                       |

Table 2
Properties of Magnetic Energy in Simulated Galaxy Clusters

| Name | $E_M$ (erg)$^a$ | $E_{M200}$ (erg)$^b$ | $\alpha^c$ | $E_{M200} / E_K$ | $\gamma^d$ |
|------|----------------|----------------------|------------|------------------|------------|
| R1   | 6.17e59        | 9.55e60              | 1.00       | 0.00814          | 0.44       |
| R2   | 4.85e59        | 1.34e60              | 0.295      | 0.00306          | 0.65       |
| R3   | 5.57e59        | 9.10e59              | 0.601      | 0.00240          | 0.57       |
| R4   | 5.32e59        | 4.19e59              | 0.693      | 0.0122           | 0.3        |
| R5   | 6.37e59        | 3.07e59              | 1.436      | 0.0113           | 0.46       |
| R6   | 5.94e59        | 8.62e58              | 1.445      | 0.0113           | 0.45       |
| U1a  | 6.32e59        | 2.99e60              | 0.131      | 0.00119          | 0.56       |
| U1b  | 5.83e59        | 5.88e60              | 0.277      | 0.00248          | 0.55       |
| U2a  | 3.32e59        | 8.90e58              | 3.38e-2    | 1.77e-4          | 0.67       |
| U2b  | 6.01e59        | 3.68e57              | 1.53e-3    | 7.19e-6          | 0.81       |
| U3   | 4.74e59        | 4.99e59              | 0.175      | 8.21e-4          | 0.43       |
| U4   | 5.35e59        | 1.25e60              | 0.603      | 0.00513          | 0.74       |
| U5   | 5.35e59        | 6.07e59              | 0.350      | 0.00224          | 0.59       |
| U6   | 5.21e59        | 3.29e59              | 0.382      | 0.00259          | 0.53       |

Notes.

$^a$ Magnetic energy at the end of injection.

$^b$ Magnetic energy inside $R_{200}$ at $z = 0$.

$^c$ $\alpha$ in Equation (1), proportionality parameter between magnetic energy and cluster mass square.

$^d$ Ratio of magnetic to kinetic energy inside $R_{200}$ at $z = 0$.

$^e$ Best fit of $\gamma$ in relation between the magnetic field strength and the gas density ($B \propto n^\gamma$).

match results from observations. On the other hand, very small seed fields from some first principle mechanism, such as the Biermann battery effect, are also studied (Kulsrud et al. 1997; Xu 2009) in galaxy cluster simulations. Kulsrud et al. (1997; and Ryu et al. (2008) suggested that very weak seed fields can carry large amounts of magnetic energy and flux (Burbidge 1959; Kronberg et al. 2001; Croston et al. 2005; McNamara & Nulsen 2007). The magnetization of the ICM and the wider intergalactic medium by AGNs has been suggested on the energetic grounds (Colgate & Li 2000; Furlanetto & Loeb 2001; Kronberg et al. 2001), without details of the physical processes of magnetic field transportation and amplification. Through cosmological MHD simulations, Xu et al. (2009) showed that magnetic fields injected from a single AGN into a local region can be sufficient to magnetize the whole cluster to the micro Gauss level by the operation of small-scale dynamo (Brandenburg & Subramanian 2005; Subramanian et al. 2006). Recently, Sur et al. (2010) used MHD simulations to show that same process can also operate during the formation of first stars. Small-scale dynamo may be an important process in the generation of magnetic fields in various cosmic objects (Schleicher et al. 2010).

In the first paper (Xu et al. 2010) of this study, we studied the magnetic field evolution in a single massive, relaxed galaxy cluster with different AGN-injected energies and injection redshifts. That paper found that, as long as the magnetic fields are injected before the active merger period during the cluster formation history, the AGN magnetic fields can be spread throughout the whole cluster and get substantial amplification. The final magnetic fields are weakly dependent on the amount of initial magnetic fields. But the behavior of magnetic fields in clusters of different masses and at various dynamical states, young (unrelaxed) or old (relaxed) clusters, is still not well studied.

In this paper, we perform a series of high-resolution adaptive mesh refinement (AMR) MHD simulations of 12 galaxy clusters of different masses with initial magnetic fields injected by an AGN. This allows us to investigate the robustness of magnetizing the ICM using the AGN magnetic fields and address additional questions that are not examined with a single cluster. We explore the properties of magnetic field distribution and their evolution in the ICM of those clusters in different dynamical states during their formation histories. The organization of this paper is as follows. In Section 2, we provide the details of the simulation setup, including the cluster formation and the magnetic fields injection. We then summarize the main results in Section 3. We present the detailed spatial distribution of magnetic fields, evolution of the magnetic energy, and the radial profiles of magnetic fields strength. We also present and discuss the properties of synthetic FRM of our simulated clusters. In Section 4, we present a summary of the main findings and conclusions.

2. BASIC MODEL AND SIMULATIONS

We have performed self-consistent AMR cosmological MHD galaxy cluster formation simulations of a set of clusters with
initial magnetic fields injected by an AGN, using cosmological MHD code ENZO+MHD (Collins et al. 2010). The simulation setup is the same as that in Xu et al. (2010). The initial conditions are generated from an Eisenstein & Hu (1999) power spectrum. The simulations use a $\Lambda$CDM model with parameters $h = 0.73$, $\Omega_m = 0.27$, $\Omega_b = 0.044$, $\Omega_\Lambda = 0.73$, and $\sigma_8 = 0.77$. These parameters are close to the values from recent WMAP 3 results (Spergel et al. 2007). Initial conditions from different random seeds are used to generate different clusters. The simulation volume of each run is $256\, h^{-1}$ Mpc on a side, and it uses a $128^3$ root grid and two-level nested static grids in the Lagrangian region where the cluster forms. This gives an effective root grid resolution of $512^3$ cells ($\sim 0.69$ Mpc) and dark matter particles of mass resolution of $1.07 \times 10^{10}\, M_\odot$. During simulations, eight levels of refinement are allowed beyond the root grid, for a maximum spatial resolution of $7.8125\, h^{-1}$ kpc.

The simulations are evolved from redshift $z = 30$ to $z = 0$ using an adiabatic equation of state, with $\gamma = 5/3$. The simulations do not include other physics, such as radiative cooling or star formation feedback, as they are not important to the majority of the dynamics of cluster formation. Here, we have simulations of 12 galaxy clusters with mass ranging from $9.9 \times 10^{13}$ to $1.9 \times 10^{15}\, M_\odot$ at $z = 0$. In previous studies (Xu et al. 2010), we have shown that the magnetic field evolution is neither sensitive to the injection redshift between $z = 3$ and $z = 1$ nor to the injected AGN magnetic energy, so in this study we have only one injected AGN magnetic energy and a single injection time. We “turn-on” the AGN with magnetic field injection at redshift $z = 3$ in the most massive halo (or the

Figure 1. Projected baryon density for relaxed clusters in group 1 at different redshifts. The first column is projections at the time of injection, and each image covers a region of $32.0\, \text{Mpc} \times 32.0\, \text{Mpc}$ comoving. The second column shows at $z = 2$ and each image size is also $32.0\, \text{Mpc} \times 32.0\, \text{Mpc}$ comoving. The third, fourth, and fifth columns are images at $z = 1$, $z = 0.5$, and $z = 0.25$, respectively. The plot sizes are $16.0\, \text{Mpc} \times 16.0\, \text{Mpc}$ comoving. The final column shows projections at $z = 0$. Each image covers an area of $8.0\, \text{Mpc} \times 8.0\, \text{Mpc}$. The first panel in each row is marked with the respective runs. The color range of all plots is from $1.0 \times 10^{-4}$ to $1.0 \times 10^{-2}\, \text{g cm}^{-2}$.

(A color version of this figure is available in the online journal.)
The initial magnetic fields are injected into the ICM locally assuming that they are from an AGN (see description in Xu et al. 2008, 2009), based on a magnetic tower model (Li et al. 2006). The injected magnetic energy is $\sim 6 \times 10^{59}$ erg for all runs. Based on the dynamical states of these simulated clusters, these 12 clusters fall into two groups at $z = 0$, each having six clusters. We consider the clusters that have more than half of their final masses by $z = 0.5$ as relaxed clusters, and the clusters that gain more than half of their final masses from $z = 0.5$ to $z = 0$ as unrelaxed clusters. Group 1 is the relaxed clusters. They are labeled as R1 to R6, in the order of their final masses. Group 2 is the unrelaxed clusters. They are labeled as U1 to U6, also in the order of their final masses. For two of the unrelaxed clusters (U1 and U2) we have performed two simulations, with magnetic energy injected into different progenitor halos. They are labeled as U1a, U1b, U2a, and U2b, respectively. The reason that we have injections in different locations is because the choice of initial magnetized halo turns out to play an important role in the final magnetism of these two clusters. So we have a total of 14 simulations. The properties of the injection halos and the final clusters are summarized in Table 1, while the injection magnetic energies are listed in Table 2.

The AMR settings are the same as in Xu et al. (2010). The AMR is applied only in a region of $(\sim 50 \text{ Mpc})^3$ where the galaxy cluster forms. During the course of cluster formation before the magnetic fields are injected, the refinement is controlled by baryon and dark matter overdensity. After magnetic field injection, all the regions where magnetic field strength is higher than $5 \times 10^{-8}$ G are refined to the highest level, with 7.81 $h^{-1}$ kpc resolution. The data analysis in this paper was performed using yt$^4$ for Enzo (Turk et al. 2011).

There are limitations with our current simulations, which should be kept in mind when interpreting the results from these

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4 http://yt.enzotools.org
Figure 3. Projected magnetic energy density for relaxed clusters at different redshifts. The first column shows at $z = 2$ and each image size is 32.0 Mpc $\times$ 32.0 Mpc comoving. The second, third, and fourth columns are images at $z = 1$, $z = 0.5$, and $z = 0.25$, respectively. The plot sizes are 16.0 Mpc $\times$ 16.0 Mpc comoving. The final column shows projections at $z = 0$. Each image covers an area of 8.0 Mpc $\times$ 8.0 Mpc. The first panel in each row is marked with the respective runs. The color range is from $1.0 \times 10^8$ to $1.0 \times 10^{12}$ erg cm$^{-2}$.

(A color version of this figure is available in the online journal.)

simulations. The highest resolution of $\sim 10$ kpc, which already made these simulations very large and very computationally expensive, is close to the characteristic scale of the ICM magnetic fields obtained from observations. Therefore, our simulations miss some small-scale features of the magnetic fields. Higher resolution simulations are underway. In addition, the MHD treatment without any kinetic effects in our simulations are not enough to completely understand the magnetic properties in the ICM. In some situations, the difference introduced by kinetic effects may be dramatic. For example, when effects of anisotropic pressure is included in a weakly collisional plasma, growth rate of magnetic field strength may be much higher (Schekochihin & Cowley 2006; Schekochihin et al. 2008). Unfortunately, the microphysical processes are still impossible to simulate self-consistently in cosmological simulations with current computational capabilities.
3. RESULTS

3.1. Formation of the Galaxy Clusters and Evolution of Magnetic Field Distribution

We first briefly show the formation histories of our simulated clusters. The hierarchy formation histories of our simulated clusters are presented by plotting the projected gas densities at various redshifts from $z = 3$ to $z = 0$. Relaxed clusters are plotted in Figure 1, and the unrelaxed clusters are shown in Figure 2. The clusters usually undergo numerous mergers at redshift between 3 and 0.5. For redshift less than $\sim 0.5$, the clusters start to relax unless some rare big mergers happen. The dynamically old and relaxed clusters in group 1 have experienced major mergers

![Figure 4. Same as Figure 3, but for unrelaxed clusters in group 2. (A color version of this figure is available in the online journal.)](image)
several Gyr before the end of the simulation, and have been
dynamically relaxed for some time before $z = 0$. In contrast,
the younger, unrelaxed clusters of group 2 have experienced
major mergers closer to the end of the simulations. As we have
mentioned in the previous section, the clusters in group 1 have
more than half of their final masses at $z = 0.5$, whereas the
clusters in group 2 more than double their masses from $z = 0.5$ to $z = 0$ by big mergers. From the shapes of the projected
density, some clusters of group 2 look relaxed, e.g., cluster U1,
though they have just finished a very big merger and their ICM
motions are still quite active. The cluster U2 is undergoing active
mergers after $z = 0.25$ and is the dynamically youngest cluster
in our simulations. This makes the evolution of magnetic fields
in U2a and U2b very different from other runs.

Figures 3 and 4 show the projected magnetic energy densities.
Magnetic fields mostly follow the motion of the halos in which
magnetic fields are injected and may move a long distance
during the cluster formation. No matter where the magnetic

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Evolution of total magnetic energy of the simulations, the upper panel shows relaxed clusters, while the bottom panel shows the unrelaxed clusters. (A color version of this figure is available in the online journal.)}
\end{figure}
fields are injected, the final magnetic fields tend to distribute around the cluster centers at $z = 0$. These plots clearly show that mergers, especially major mergers, spread the magnetic fields throughout the clusters. So the distribution of magnetic fields are effected when these big mergers happen during the cluster formation history. There is a clear trend that the sizes of the magnetized areas and their associated magnetic energy densities are proportional to the sizes of their host halos. This is no surprise since larger clusters, which are formed by more mergers and have higher turbulence level to diffuse, amplify and maintain their magnetic fields.

Magnetic fields have already been spread to a large area of the whole clusters when simulations stop at $z = 0$ in all runs, except for runs U2a and U2b. But the distribution of magnetic fields can be quite different from that of the ICM gas if major cluster mergers have occurred recently. In such case, the magnetic field strength may peak away from the cluster centers. Magnetic fields in larger clusters, which are less affected by late time small mergers, are distributed more regularly.

In most runs, the halo with the initial magnetic injection grows fast and becomes the major progenitor of the clusters during their formation histories, so their magnetic field evolution and distribution are similar within their groups. But that is not true in three clusters, R2, U1, and U2. For cluster R2, though it is well formed before $z = 0.5$ and has relaxed at final output, its magnetized halo does not merge with the major one until $z \approx 1$. So its magnetic fields cannot spread to a large volume and get amplified in the early time. This makes its magnetic fields weak and only locally distributed as a large relaxed cluster. For the two unrelaxed clusters U1 and U2, they do not have a single major halo during their cluster formation until very low redshift. Initial magnetic fields are then injected into two different halos to see the different magnetic filed evolution. The cluster U1 is finally formed by the merging of two similar size sub-clusters at $z \sim 0.2$. In runs U1a and U1b, we initially magnetize one of these two sub-clusters, respectively. Their late major merger does not have enough time to spread their magnetic fields to the other parts of the cluster. The cluster U2 is formed by active mergers of several sub-clusters at very low redshifts. Runs U2a and U2b have two of them magnetized initially. In both runs, the lack of big mergers in the early time causes the magnetic fields to have much less amplification, and their final magnetic fields are very weak and locally distributed at $z = 0$. The magnetic fields in run U2b are so weak that they are barely seen in Figure 4.

3.2. Magnetic Energy Evolution

We present the evolution of the total magnetic energy of all the simulations in Figure 5, separated into two groups of different dynamical states. The magnetic energy generally decreases rapidly initially, for a few hundred million years, because of the rapid expansion of the initial magnetic structure. It typically takes about 1–2 Gyr for the magnetic fields to expand in the ICM to a large volume to catch the turbulent motions and to be amplified. We inject a large amount of magnetic energy into the system, which may be much more than the magnetic energy that some small halos, such as in cluster R6, can maintain. In such cases, their magnetic energies keep decreasing until they drop to levels such that their magnetic fields can be sustained in their host halos by the turbulence. After that, the magnetic energy gradually increases due to the increasing size and the ICM turbulent level by continuous mergers until saturation occurs (due to lack of mergers) or the simulation ends. Although the precise evolution of magnetic fields is quite different for various runs, the fastest amplifications of magnetic fields generally happen a while (hundred million years) after the active mergers (big or continuous mergers) that assemble the major part of the clusters.

The final magnetic energies are between $4 \times 10^{57}$ and $1 \times 10^{61}$ erg. The magnetic energy is saturated (stops growing; for a detailed discussion, see Xu et al. 2010) for several Gyr for relaxed clusters in group 1. The only exception is cluster R2, in which weak magnetic fields, due to lack of early major mergers, are still being amplified long after the relaxation of the cluster. Almost all of the clusters in group 2 have major mergers at low $z$, so their magnetic energies keep increasing until simulations end, except for run U2b. For this run, its magnetic fields, which are in a very small halo before the final assembly, occupy too small a volume to get amplified effectively when the simulation ends.

Not surprisingly, the total magnetic energy is higher for the larger clusters, which have a deeper potential well, and higher thermal and kinetic energies. We plot the total magnetic energy versus the virial mass of the clusters in Figure 6 at $z = 0$. The total magnetic energy is scaled as $M^2_{\text{vir}}$ for most of the runs, except runs U2a and U2b. The total magnetic energy and the virial mass can be a single proportionality parameter $\alpha$ as

$$
\frac{E_M}{6.09 \times 10^{60} \text{erg}} = \alpha \left( \frac{M_{\text{vir}}}{10^{15} M_\odot} \right)^2,
$$

(1)

where $\alpha$ is within a range between 0.131 and 1.445 for all runs except runs U2a and U2b. The energy $6.09 \times 10^{60}$ is chosen to make $\alpha = 1$ for run R1. We summarize $\alpha$, magnetic energies, and their ratio to kinetic energies inside $R_{200\text{c}}$ of all simulations in Table 2. The coefficient $\alpha$ is mostly decided by the cluster formation history. They are generally higher for the relaxed clusters in group 1 than for the dynamically younger clusters in group 2. The magnetic energies of runs U2a and U2b of the youngest cluster are far away from the $E_M \sim M^2$ scaling. This is because their magnetic fields do not get amplified until the late active mergers, and their current magnetic energies are limited by their small halos before the major active mergers.

Though the processes of cluster formation and magnetic field evolution are highly nonlinear and complex, this scaling relation between magnetic energy and virial mass can be qualitatively approximated as $E_M \sim M^\alpha$ with $0.131 < \alpha < 1.445$. This indicates the magnetic energy is a key ingredient in the process of cluster formation and may play an important role in the distribution and evolution of the magnetic fields in clusters.
understood. Using an overly simplified isothermal model, the thermal and kinetic energies of galaxy clusters are proportional to $M_{\text{vir}}^{5/3}$ (Bryan & Norman 1998) with a radial density profile as $\rho \propto r^{-2}$ and a flat velocity dispersion. These relations were numerically confirmed by Vazza et al. (2006, 2011) using both smoothed particle hydrodynamics (SPH) and AMR codes. Since the clusters are not exactly isothermal, especially in the outer part of the clusters, these scalings should be modified somewhat. The profiles of the density and the velocity dispersion deviate from the isothermal distribution as $\rho \propto r^{-3}$ and $\sigma \propto r$ (Navarro et al. 1995; Sunyaev et al. 2003) at large radii. In such a case, we find that the total kinetic energy is approximately proportional to the square of the virial masses in our simulations. As the magnetic energies in clusters in similar dynamical states are proportional to the kinetic energies with small scattering related to formation and magnetization histories (because magnetic power spectra of all simulations have a same shape and their levels are simply determined by the levels of the kinetic ones; see Section 3.4), the magnetic energy is then proportional to the square of the cluster mass.

Because the magnetic energy in a halo is proportional to the square of it mass, the magnetic fields in a massive cluster are

Figure 7. Volume histogram of kinetic plasma $\beta$ ($= e_K/e_M$) inside the clusters’ virial radii at $z = 0$. Relax clusters are shown in the top panel and the unrelaxed clusters are shown in the bottom panel. (A color version of this figure is available in the online journal.)
Figure 8. Spherically averaged radial profiles of rms magnetic field strength of different clusters. Relax clusters are shown in the upper panel and the unrelaxed clusters are shown in the bottom panel. The x-axis is normalized by their virial radii. (A color version of this figure is available in the online journal.)

much larger than the magnetic fields residing in its progenitor halos, so the major contributing factor to the final cluster magnetic fields is from the dynamo process after a majority of the cluster has formed. It also suggests that additional magnetic fields from more AGNs or regular galaxies in smaller halos may have only small impact on the final magnetic fields in a cluster.

As listed in Table 2, the magnetic energy in a cluster is only a small fraction of its kinetic energy. For relaxed clusters, their magnetic energies are about 1% of their kinetic energies inside their virial radii. These ratios drop to about 0.1% for the dynamical younger clusters, and even smaller for the recently formed cluster U2. The local magnetic energy is much smaller than the kinetic energy in most of the cluster regions as well. To show this, we plot the volume histogram of kinetic $\beta$ ($e_K / e_M$) of all clusters at $z = 0$ in Figure 7. For relaxed clusters, kinetic $\beta$ peaks at between 50 and 100, whereas peaks of kinetic $\beta$ are bigger than 100 for unrelaxed clusters. Even
for a relaxed cluster, only a small fraction of its volume has magnetic energy greater than kinetic energy. The magnetic fields are therefore dynamically unimportant in all of these simulated clusters. Several factors may contribute to the magnetic energy being only a small fraction of the corresponding kinetic energy. First, it is possible that simulation resolution is not high enough, as the corresponding numerical diffusion is large, so the turbulence decays before it has an opportunity to amplify the magnetic fields. Some of our higher resolution test runs show that there are somewhat larger amount of magnetic fields, but the total magnetic energy is still much smaller than the kinetic energy. Second, it could be that there is not enough time during cluster formation for the magnetic fields to grow in large scales, of which the eddy turnover time is $\sim$Gyr. Third, the driving from mergers is not constant and not homogeneous, and becomes weaker when the cluster gets bigger. Fourth, it is not known what the expected level of magnetic field saturation is for compressible turbulence. Simulations of supersonic and superalfvenic compressible MHD turbulence in Kritsuk et al. (2009) found that the saturated magnetic energy is much smaller than the kinetic energy if the initial fields are weak. A further study to understand why the magnetic fields saturate at a level much lower than the kinetic energy in the ICM is needed. Fifth, since we only have one seed source for magnetic fields, significant magnetic fields only fill a portion of the ICM (from 20% to 80%; see the next subsection on magnetic fields distribution). So in a case of more sources and a higher filling of magnetic fields in a galaxy cluster, its magnetic energy ratio could potentially be somewhat higher (but still much smaller that kinetic energy, at most a few percent).

3.3. Magnetic Field Distribution over the ICM at $z = 0$

3.3.1. Radial Profiles of Magnetic Fields

In Figure 8, we present the spherically rms averaged radial profiles of magnetic fields at $z = 0$. The relaxed and unrelaxed clusters are plotted in two different panels, and the radii are normalized by their virial radii. It is clear that the profiles of magnetic field strength are determined both by the cluster sizes and their dynamical states.

The magnetic field strength is generally higher for the bigger clusters and dynamically older clusters. For relaxed cluster, micro Gauss fields are present at the centers of clusters bigger than $10^{15} M_\odot$, but fields drop to about $0.5 \mu G$ for the smallest cluster of $10^{14} M_\odot$. The magnetic field profiles of relaxed clusters in group 1 are more regular as a function of radius, whereas the magnetic field profiles of dynamically younger clusters in group 2 are obviously disturbed by their recent big mergers. For runs U2a and U2b, because the cluster is formed so late and no significant amplification of magnetic fields has been operated, their magnetic fields are much weaker and reside only in the inner part of the cluster.

Several other MHD simulations (e.g. Dolag et al. 2002; Dubois et al. 2009), as well as the study on the rotation measures (RM) and the X-ray surface brightness correlation (Dolag et al. 2001), suggest that the decline of magnetic fields is correlated with the gas density as $n^\gamma$. Analysis of RM and
X-ray brightness data in Dolag et al. (2001) yields the $\gamma = 0.9$ for A119 and $\gamma = 0.5$ for 3C129 with large uncertainty. We fit our magnetic field radial profile with the gas density profile and list the best-fitted results in Table 2. The $\gamma$ in our simulations scatters between 0.3 and 0.81, which is consistent with the results from Dolag et al. (2001). Relaxed clusters usually have smaller $\gamma$, so have flatter magnetic field profiles as they have more time to amplify their magnetic fields in the outer part by the ICM turbulence after major mergers. However, the reliability of our results may be limited by the way we magnetized clusters; we need simulations with many AGNs in one cluster to get more reliable $n\gamma$ profiles. In addition, since this result is obtained by fitting the averaged radial profiles of the magnetic field strength and the gas electron density, it does not mean that there is a simple correlation between the magnetic field strength and the gas density throughout the cluster.

### 3.3.2. Magnetic Field Spatial Distributions

We plot the volume histograms and complementary cumulative volume ratio histograms of magnetic field strength inside the virial radii for all simulations at $z = 0$ in Figure 10. The magnetic field fillings are quite different for the relaxed and unrelaxed clusters. For dynamically older clusters, most volumes inside the virial radii are filled with magnetic fields. Magnetic fields stronger than $10^{-8}$ G typically fill more than 75% of the cluster volume for group 1 except for run R2 and less than 50% for group 2 except for run U5. For run R2 of group 1, because the magnetized halo merges with the bigger halo after $z = 1$, its magnetic field volume filling is consequently smaller. Once the magnetic fields are well spread throughout the clusters and get amplified, magnetic field strength distribution peaks between 0.1 and 0.3 $\mu$G. Larger and older clusters have much higher peaks as well as longer tails of stronger magnetic fields. Runs U2a and...
U2a and U2b have very weak magnetic fields that only fill very small volumes.

We also plot the two-dimensional distribution of the magnetic field strength versus the gas density inside their virial radii in Figure 10, showing how magnetic fields distributed over the ICM plasma. There is no obvious correlation between the field strength and the gas density. The distribution is similar for clusters of similar sizes. Most of the magnetic field strength is between 0.1 to a few micro Gauss and are mixed with gas over a wide range of densities. This casts doubts on cluster magnetic field modeling when simple correlation between $|B|$ and ICM density is assumed.

3.4. Kinetic and Magnetic Energy Density Power Spectra

The kinetic and magnetic energy density power spectra of all clusters at $z = 0$ are shown in Figure 11, which are computed from boxes of $512^3$ cells ($\sim (5.5 \, \text{Mpc})^3$) in the highest level enclosing the clusters. The ICM turbulence is represented by Kolmogorov-like spectra in kinetic energy. These kinetic spectra are also seen from pure hydrodynamics simulations of galaxy clusters (Vazza et al. 2009). All magnetic spectra are in a similar shape and follow the $k^{3/2}$ Kazantsev law in the large scales. The Kazantsev spectrum, which is the prediction of small-scale dynamo theory in the kinematic regime (see Brandenburg & Subramanian 2005), is also found in simulations of a collapsing Bonnor–Ebert sphere in Federrath et al. (2011). These magnetic spectra in our simulations show that the small-scale dynamo (see Xu et al. 2010, for detailed discussions) does operate in all our simulated clusters. For dynamically young clusters, some (like cluster U4) of their power spectra are disturbed by the recently mergers.

For the relaxed or dynamically older clusters, the magnetic fields have enough time to be amplified, their magnetic energy densities are close to the kinetic energy densities in small scales. One possible reason that the magnetic energies in smaller scales are smaller than the kinetic energies is because the magnetic fields do not fill all the space of the clusters. For the recently merged clusters, the magnetic fields do not have enough time to spread throughout the newly formed clusters and be completely amplified by the ICM turbulence, so their magnetic energies are much smaller than the kinetic ones even in the small scales.

3.5. Faraday Rotation Measurement from Simulations

The FRM is a key method for measuring cosmic magnetic fields and has provided important information on cluster magnetic fields. The RM maps have been used not only to estimate the strength of magnetic fields (see review by Carilli & Taylor 2002) but also the turbulent structure of the fields (Vogt & Enßlin 2005; Enßlin & Vogt 2006) in the ICM. We compute the RM maps using the magnetic field and free electron density distribution from our simulations by integrating 8 Mpc over the clusters centered at each cluster’s center along the y-axis at $z = 0$. We show our synthetic RM maps in Figure 12. Though the basic features of the RM distribution are similar to those from previous studies (Xu et al. 2009, 2010), clusters of different size and/or at different dynamical states have quite different RM distribution in their absolute values, cover areas, and structure scales. The morphologies of the RM maps reflect the dynamical states of the clusters and their merger histories. There is a clear trend that there are more small-scale patterns in the dynamically old relaxed clusters than in young clusters. This is because they have more time for the magnetic field amplification in small scales after major mergers. On the other hand, there are more long filaments on the younger, unrelaxed clusters reflecting their recent mergers. There are very long filaments ($> 1 \, \text{Mpc}$) in runs U1a and U1b associated with their recent large head-on mergers. It is interesting to see that the RM maps are quite different between these two runs, of which the pre-merger magnetic fields reside in different sub-clusters, though the gas dynamics of these two runs are almost identical. This shows that the magnetism history of the cluster also plays an important role in determining their RM distribution.

The two-dimensional azimuthally averaged radial profiles of the absolute values of these FRM ($|\text{RM}|$) are plotted in Figure 13 and the radial profiles of the standard deviation of the RM are shown in Figure 14. The $|\text{RM}|$ profiles resemble the magnetic field strength profiles with steep slopes, as the ICM gas density decreases with the radius. These $|\text{RM}|$ profiles are roughly similar to the pattern from observational data in Clarke et al. (2001). The $\sigma_{\text{RM}}$ profiles are also consistent with the recently observational results in Govoni et al. (2010).
Figure 12. Faraday rotation measurement of the clusters by integrating through the cluster on the y-direction. It covers a region of 3 Mpc × 3 Mpc at z = 0. The color range shown is from −500 (blue) to 500 (red) rad m⁻². The upper two rows are relaxed clusters, and the rest are unrelaxed clusters. (A color version of this figure is available in the online journal.)

We also plot the area histograms of RM and the complementary cumulative histograms of |RM| inside 500 kpc central circles of the clusters in Figure 15. Relaxed clusters generally have more areas covered by significant |RM|. For all cases, the distribution of positive and negative RM is roughly symmetric. This is because there is no net magnetic fluxes in the clusters, for the model of field injection we have used. The RM area histograms are similar for clusters of similar sizes and dynamical states, though their RM maps may look quite different from their different formation or magnetism history. This suggests that the histograms of RM distribution are not sensitive to the cluster merger and magnetism history, which can be reflected by their RM filament and patchy structures.

4. CONCLUSIONS

In this paper, we report an ensemble of simulations of magnetic field evolution in galaxy clusters with a wide range of masses between $1 \times 10^{14}$ and $2 \times 10^{15} M_\odot$ in various dynamical states. With similar amounts of initial magnetic fields injected from a single AGN at a high redshift, all clusters are eventually filled with micro Gauss magnetic fields, except for dynamically very young clusters. The power spectra of kinetic...
Figure 13. Azimuthally averaged radial profiles of $|RM|$ of the RM maps shown in Figure 12. The top panel shows the relaxed clusters, while the bottom panel shows that unrelaxed clusters. The $x$-axis is normalized by the clusters’ virial radii.

(A color version of this figure is available in the online journal.)

energy density show that the ICM is in a turbulent state, while the spectra of magnetic energy density show that the small-scale dynamo process is being driven by the ICM turbulence. This result, along with the previous study of a single cluster with the magnetic field injections of different amounts of magnetic energy and at different redshifts (Xu et al. 2010), suggests that magnetization of galaxy clusters by the operation of small-scale dynamo with the seed magnetic fields from an AGN is very robust, and it produces magnetic fields consistent with observed magnetic fields.

The magnetic field evolution and distribution are decided both by the masses of the clusters and their dynamical formation histories. The total magnetic energy is approximately scaled as the square of the virial mass of the cluster, while the dynamically older (relaxed) clusters usually have more magnetic fields. This implies that the cluster magnetic fields are mostly determined by the dynamo process of the ICM turbulence generated by the hierarchical mergers. Additional magnetic fields from more AGNs or smaller cluster-forming halos will not have a major impact on the final magnetic fields in a massive cluster. The $\gamma$ in the scaling relation between magnetic field and gas density radial profiles ($|B| \propto n^\gamma$) range between 0.3 and 0.81 for our simulated clusters, while relaxed clusters have flatter magnetic fields profiles. In addition, the relaxed clusters usually have self-similar magnetic field radial distribution, whereas the field distribution in younger unrelaxed clusters is disturbed by their recently mergers. Though our simulated clusters only have initial magnetic fields from a single local source, most volumes in the simulated clusters are well magnetized.

We also studied FRMs obtained from the magnetic field and gas density distribution in our simulated clusters. They are also determined by both the cluster sizes and their dynamical states. The radial profiles of $|RM|$ resemble the profiles of the magnetic field strength and are consistent with the pattern from the observational data. The RM maps reflect the recent cluster mergers as well as the cluster magnetism history. There are very long filaments in the RM maps in the recently merged clusters, while their small-scale patchy bands reflect the ICM turbulence. For the same cluster but with magnetic fields injected in different locations very different distributions of RM are observed. This suggests that RM distribution may be a good probe not only for the cluster formation but also its magnetism history. A detailed study on the relation of RM from simulated clusters with their ICM turbulence will be presented in a forthcoming paper.

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Figure 15. Histogram of RM (top) and complementary cumulative histogram of |RM| (bottom) of the central circle of 0.5 Mpc radius of the RM maps shown in Figure 12. The left panel shows the relaxed clusters and the right panel shows the unrelaxed clusters.

(A color version of this figure is available in the online journal.)

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