EARLY STARBURSTS AND MAGNETIC FIELD GENERATION IN GALAXY CLUSTERS

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ABSTRACT

We propose a mechanism for the early generation of the mean intracluster magnetic field in terms of magnetized galactic winds. These winds are the result of starburst phases of the cluster galaxies, assumed to produce the predominant population of early-type galaxies in mergers of gas-rich progenitors. After further cluster contraction, typical field strengths are \(10^{-7}\) G. This estimate may increase to the level of \(10^{-6}\) G if more extreme galactic parameters and subsequent shear amplification of the field are considered. The topology of the field is one of almost unconnected wind bubbles with Parker-type spiral field configurations over scales of the distance between galaxies. Further cluster accretion, which continues chaotically in space and time up to the present, will perturb these “large-scale” mean fields on smaller or at best comparable spatial scales. The small-scale fields in the resulting turbulent fluctuation spectrum should be able to confine relativistic particles over times longer than the age of the universe. The nonthermal particle content of galaxy clusters should therefore also have a “cosmological” hadronic component generated during the early starburst phase of the member galaxies. Already by itself it implies a nonthermal energy fraction of about 10% for the intracluster gas that should then be detectable by future \(\gamma\)-ray telescopes.

Subject headings: acceleration of particles — cosmic rays — galaxies: clusters: general — galaxies: starburst — intergalactic medium — magnetic fields

1. INTRODUCTION

Rich clusters of galaxies are the largest gravitationally bound structures in the universe and should confine a representative fraction of its mass. Therefore, the study of their dynamical properties and radiation content should allow, among other things, interesting cosmological conclusions on the relative amounts of visible and dark baryonic matter and of nonbaryonic matter (e.g., White & Fabian 1995; Turner 1999).

Another basic characteristic, resulting from energetic particle confinement, is the ratio of nonthermal to thermal energy in these objects. To a significant extent that ratio should be predetermined during the epoch of early starburst activity and thus should preserve the energetic history of cluster formation. The necessary confinement of the nonthermal particle components is intimately related to the existence of strong and chaotic magnetic fields in the intracluster medium (ICM), and we shall propose physical mechanisms for their early generation as well as for their present fluctuations.

In principle, detailed ab initio simulations of the dynamics of cluster formation under the dominant gravitational influence of the dark matter component (see, e.g., Kauffmann et al. 1999) should establish the overall cosmological framework for the present considerations. We start rather in a complementary way with the discussion of a simplified model of cluster formation and of chemical enrichment of the intracluster gas. It has the advantage that it directly allows a discussion of the physical processes of nonthermal particle production and confinement. The main part of the paper concerns a proposal of cluster magnetic field generation in terms of galactic winds due to early starbursts and their amplification effect on magnetic fields drawn out from the progenitors of today’s cluster galaxies into intracluster space. It is argued that, because of these dynamical processes, there is no need for the operation of a dissipative turbulent dynamo in the ICM. The ongoing cluster accretion naturally leads to a strong fluctuating part of the intracluster magnetic fields. A detailed discussion of the nonthermal radiation from galaxy clusters will be given in a separate paper (Atoyan & Völk 2000).

2. RICH CLUSTERS

We shall be concerned here with rich clusters, i.e., conglomerates with typically more than 100 member galaxies. They have typical radii \(R_{cl} \sim\) a few Mpc and baryonic masses \(M_{cl} \sim 10^{14} - 10^{15} M_\odot\). Many such clusters are rather evolved and contain predominantly early-type S0 and E galaxies, at least in their inner parts. Examples for bright and relatively nearby clusters of this type are the Perseus and Coma clusters with distances \(d \sim 100\) Mpc. The Perseus Cluster is the brightest cluster in soft X-rays. The large X-ray luminosity is due to the very hot \((T \sim 10^7 - 10^8\) K), massive \((M_{gas} \sim\) a few times \(\sum M_{gas}\)), and metal-rich \([(\text{Fe})_{\odot} \approx 0.35(\text{Fe})_{\odot}]\) ICM gas (e.g., Böhringer 1996). As a consequence, the gas pressures are extremely high, with \(nT\) ranging from \(10^3\) to \(10^5\) K cm\(^{-3}\).

2.1. Cluster Formation

The metallicity of the ICM gas, for instance, in terms of the fractional ICM iron mass, is correlated with the total
optical luminosity in the E and S0 galaxies of rich clusters (Arnaud et al. 1992). The correlation supports the view that early starbursts due to galaxy-galaxy interactions of gas-rich progenitors have produced a large number of core-collapse supernovae (for simplicity referred to here as SNe) due to massive stars. They should have heated the originally present interstellar gas and generated violent galactic winds that removed the interstellar medium, leaving gas-poor E and S0 galaxies behind. This mass loss should have led to the observed strong chemical enrichment of the ICM gas.

We also conjecture that the ionizing radiation, the winds, and the large-scale shocks from these early galaxy mergers, together with the hard radiation from active galactic nuclei, strongly heated the remaining primordial ICM gas and thus prevented further galaxy formation. A quantitative discussion of the dynamical prerequisites for galactic winds and of the total number of SNe in clusters is given by Völk, Aharonian, & Breitschwerdt (1996, hereafter V96).

The total number of SNe since galaxy formation in the cluster, roughly a Hubble time $T_h \simeq 1.5 \times 10^{10}$ years ago, is then given by

$$N_{SN} = \int_{-T_h}^0 dt \frac{0.35[Fe]_D M_{cl}}{\delta M_{Fe}},$$

where $\delta M_{Fe}$ is the amount of iron produced per event. In such starbursts we predominantly expect core-collapse SNe from massive progenitor stars to occur, with $\delta M_{Fe} \simeq 0.1 M_\odot$ on average. For the Perseus Cluster this implies $N_{Perseus} \sim 3 \times 10^{12}$. The corresponding total energy input into the interstellar medium is $N_{SN} E_{SN} \sim 3 \times 10^{63} E_{51}$ ergs, where $E_{51} = E_{SN}/10^{51}$ ergs is the average hydrodynamic energy release per SN in units of $10^{51}$ ergs.

Assuming that the early starbursts occur at a typical redshift of $z \sim 2$ as a result of the merging of gas-rich progenitors in an overdense protocluster environment (Steinmetz 1993), with a duration of $T_{SB} \lesssim 10^9$ yr, we obtain

$$\left(\frac{N_{Perseus}/N_{gal}}{T_{SB}}\right) \gtrsim 100 v_{SNMilky Way},$$

where $v_{SNMilky Way}$ is taken as $1/(30$ yr) and $N_{gal} \simeq 500$ denotes the number of galaxies in the Perseus Cluster. As an example, we can look at the archetypical contemporary starburst galaxy M82. It has a current SN rate $v_{SNM82} \sim 10 v_{SNMilky Way}$, a wind velocity $v_{wind} \sim 2300$ km s$^{-1}$, and a mass-loss rate $\dot{M} \sim 0.8 M_\odot$ yr$^{-1}$ (Breitschwerdt 1994). The starburst nucleus of M82 is characterized by the following values for the interstellar gas temperature $T$, gas density $n$, and thermal gas pressure $p$ at the base of the wind: $T_{base} \sim 10^8$ K, $n_{base} \sim 0.3$ cm$^{-3}$, and $p_{base}/k_B \sim 10^7$ K cm$^{-2}$ (Schaaf et al. 1989). Since the thermal ICM gas pressure in the Perseus Cluster is $p_{ICM}/k_B \sim 10^4$ K cm$^{-2}$, it is clear that an object like M82 could readily drive a wind even against the present-day ICM pressure. At the galaxy formation epoch the ICM pressure should have been much smaller than this value.

In an expanding galactic wind flow the SN-heated gas will cool adiabatically to quite low temperatures. However, it will be reheated in the termination shock, where the ram pressure of the wind adjusts to the ICM pressure. Much beyond this point the ejected galactic gas is expected to slowly exchange energy and some metal-rich material with the unprocessed ICM gas.

### 2.2. Nonthermal Particle Production

Cluster formation also implies the production of a strong nonthermal component of relativistic particles. They will be accelerated during the early phase and presumably also in later accretion events that have shock waves associated with them. In the supernova remnants (SNRs) the main acceleration should occur at the outer shock, with a very high efficiency of $\sim 10\%$ (Drury, Markiewicz, & Völk 1989; Berezko & Völk 2000), the rest of $E_{SN}$ going into the thermal gas ($\sim 10\%-20\%$) (Dorfi 1993) and radiation ($\gtrsim 70\%$). However, since the particles are ultimately removed from the galaxies in a strong galactic wind (see V96 and § 3 below), they will cool adiabatically like the thermal gas and transfer their energy to the kinetic energy of the wind flow. As a consequence, the original SNR-accelerated particles should constitute a negligible fraction of the present-day nonthermal particle content of the cluster. But this is not the end of the story. At distances of $\sim 100$ kpc from the galaxies, fresh particle acceleration will occur at the strong galactic wind termination shocks (Fig. 1). We estimate the overall acceleration efficiency in these shocks to be again of the order of $10\%$.\(^1\) Over the early phase of galaxy formation, with the use of our estimate for the total number of SNe, this should result in a total gas internal energy in the postshock region $E_{gas}^{SW} \sim$ a few times $10^{56}$ ergs and a nonthermal energy $E_{NR}^{SW} \sim$ a few times $10^{41}$ ergs for a system like the Perseus Cluster, ultimately driven by star formation and the subsequent SN explosions. Since

\(^1\) Note that this acceleration efficiency might also be lower, if the termination shocks were essentially perpendicular.
the confinement time in the cluster (see next subsection) exceeds the cluster lifetime, the energy spectrum of these particles in the ICM is basically the same as the source spectrum at the termination shocks. In cosmic-ray (CR) parlance these are cosmological CRs.

Since the galaxies are distributed across the cluster quasi-uniformly, this should originally also be true for the nonthermal particle population. The ensuing gravitational contraction/accretion of the cluster will subsequently energize CRs and thermal gas at least adiabatically or, more likely, will shock accelerate/irreversibly heat both components so that finally the total energy $E_{\text{CR}}$ of energetic particles should reach at least the adiabatic value $\sim 3 \times 10^{42}$ ergs $\sim (1/30)E_{\text{gas}}$ in the cluster; $E_{\text{gas}}$ now denotes the total present internal energy of the ICM gas (V96).

It is worthwhile to compare the expected nonthermal energy with the thermal energy content of the cluster galaxies. Assuming the stars internally to be in virial equilibrium and, for purposes of estimate, all of them to have a solar mass and radius, then $E_{\text{star}}^{\text{tot}} \sim (3/10)GM_{\odot}/R_{\odot} \approx 10^{48}$ ergs. For a total mass of about $10^{14}M_{\odot}$ contained in the galaxies of the Perseus Cluster, this gives a total thermal energy in stars of $\sim 10^{42}$ ergs, and thus $E_{\text{CR}} \gtrsim \sum_{\text{gal}} \sum_{\text{stars}} E_{\text{star}}^{\text{tot}}$. This means that the nonthermal ICM energy should be at least as large as the total thermal energy content of all the stars in all the galaxies together.

It has been argued more recently that, apart from star formation and overall gravitational contraction, individual giant radio galaxies should also have injected large and, in fact, comparable amounts of nonthermal particles during the lifetime of a cluster (Enßlin et al. 1997; Berezinsky, Blasi, & Ptuskin 1997). This is no doubt an important additional possibility. A weakness of this argument consists in the fact that per se it is predicated on statistical knowledge about the luminosity function for active galaxies in clusters in general and not on direct observations of the individual cluster to which it is applied.

2.3. Particle Confinement

Energetic particle confinement has been discussed in a number of papers in recent years (V96; Berezinsky et al. 1997; Colafrancesco & Blasi 1998). Here we review this important point, and in the next section we consider this point in light of the magnetic field structure.

The large-scale magnetic field in the ICM gas may be quite chaotic and not well connected over distances exceeding typical intergalactic distances. Thus, energetic particles may not readily escape from the cluster as a result of such topological characteristics. However, a consideration of pure pitch angle diffusion along straight magnetic field lines with superposed turbulent fluctuations already gives important insights into the confinement properties of galaxy clusters. Standard quasi-linear theory yields a spatial diffusion coefficient $\kappa_{||}$ along the large-scale field $B$ resulting from a power spectrum $P(k)$ of magnetic field fluctuations with wavelength $\lambda = 2\pi/k$ in the following form:

$$\kappa_{||} = \left(\frac{1}{3}\right)cr(p)\frac{B^2}{\int_0^\infty dk'P(k')}$$

where $r_r(p)$ is the gyroradius of a particle with momentum $p$, $kr_r(p) \approx 1$, and $k$ denotes the wavenumber of the field fluctuations. Let us assume a relative fluctuation field strength of order unity at the distance $1/k_0$ between galaxies, i.e., a totally turbulent field $k_0 P(k_0) \sim B^2$ on this scale and a power-law form of $P(k) = (k_0/k)^n$. Then, the diffusion time across the cluster $T_{\text{esc}} \sim \frac{R^2_{\text{cl}}}{k_0^2} > T_{\text{H}}$ for $(cp)_{\text{protons}} \lesssim 10^{17}$ eV and $(cp)_{\text{protons}} \lesssim 10^{15}$ eV for $n = 3/2$ and $n = 5/3$, respectively (V96). Also, $\tau_{\text{loss}} > T_{\text{H}}$ for nuclear collisions in the ICM gas. Therefore, except at sub-relativistic energies with their prevailing Coulomb losses, up to these energies CR hadrons should have accumulated in the cluster since the galaxy formation epoch, and that is what we called cosmological CRs before. The situation is different for relativistic electrons, which suffer radiative losses. Electrons and the nonthermal radiation from galaxy clusters are discussed extensively in the paper by Atoyan & Völk (2000).

2.4. Gamma Rays from Cosmological CRs

The accumulated cosmological CR protons and nuclei will produce high-energy $\gamma$-rays from inelastic $pp$ collisions on the intracluster gas that, in particular, lead to $\pi^0$-production and subsequent decay. Figure 2 shows the $\pi^0$-decay energy fluxes expected from the hadronic CRs of the Coma cluster with a differential energy spectrum $\propto E^{-2\nu_{\text{CR}}}$ exp $(-E/E_{\nu})$, with $\nu_{\text{CR}} = 2.1$ and an upper cutoff energy $E_{\nu} = 200$ TeV. The solid and dashed curves assume $E_{\text{CR}} = 3 \times 10^{42}$ ergs and $E_{\text{CR}} = 3 \times 10^{41}$ ergs, respectively, in an ICM with a gas density of $n = 10^{-3}$ cm$^{-3}$. Also, the EGRET upper limit by Sreekumar et al. (1996) is shown. The observed size of the radio emission produced by high-energy electrons in Coma is about half a degree. The brightness of the hadronic TeV emission should be significantly higher in the central region of the cluster since the ICM gas density strongly increases toward the center. Detection of an extended and weak $< 0.1$ crab] TeV flux by current instruments is problematic, but such fluxes are quite accessible for future imaging atmospheric Cerenkov telescope arrays like H.E.S.S., VERITAS, and CANGAROO III (see Fig. 2).
3. INTRACLUSTER MAGNETIC FIELDS

The magnetic field strengths in the ICM of rich clusters, which may be as large as $B \sim 1 \mu G$ as inferred by Faraday rotation measurements (e.g., Kronberg 1994), are not easily explained by a contemporary dissipative mechanism because present-day turbulent dynamo effects in such a large-scale system should be extremely slow. This problem is compounded by the extraordinary smallness of the expected intergalactic seed fields. Therefore, we suggest a field configuration that is due to the early formation history of galaxy clusters as discussed above; it should be preserved in its essential features to this day (Völk & Atoyan 1999). This field should still be in a state of development even at the present epoch. The model derives from the violent early galactic winds that accompany the starbursts responsible for the predominance of the early-type galaxies in rich clusters.

In a general form the ejection of galactic fields has been discussed by Kronberg (1994). For the generation of the general intergalactic magnetic field, related arguments have been advanced independently by Kronberg, Lesch, & Hopp (1999), assuming very early formation of dwarf galaxies with wind outflows at redshifts $\geq 10$.

We assume first of all that the gas-rich progenitors whose mergers supposedly constitute the building blocks for the E and S0 galaxies can be specifically pictured as protospirals that had already generated galactic magnetic fields of $\mu G$ strength. This should indeed be possible within a time of $10^8$ yr or less, i.e., a timescale of the order of a rotation period of our Galaxy or even shorter. The explanation derives from fast turbulent dynamo action that invokes buoyancy effects due to CRs that inflate the magnetic flux tubes together with magnetic reconnection over spatial scales of order 100 pc (Parker 1992). In starburst galaxies systematic dynamo effects might also play an important role (§ 3.1).

In a second stage, i.e., during the galaxy mergers, the resulting supersonic galactic winds will extend these fields from the interacting galaxies to almost intergalactic distances. In the final and by far longest stage that lasts until now, the fields should be recompressed by the contraction of the cluster to its present size. In addition, the continuing accretion of subclusters and individual galaxies constantly perturbs this field, keeping the fluctuations around this large-scale field at a high level.

The ICM fields do not reconnect on the intergalactic scale in a Hubble time. Consequently, there is no need for a continuous regeneration of these fields since their formation. However, this also implies that a topologically connected overall ICM field will on average not be formed either and that the ICM field is chaotic on a scale smaller than or equal to the present intergalactic distance.

In detail we draw on arguments that we have used in the past for the field configuration in a galactic wind from our own Galaxy (Zirakashvili et al. 1996; Ptuskin et al. 1997; see also Fig. 3). They are based on estimates of the relative amount of field-line reconnection versus the extension of Galactic field lines by a wind to “infinity” (Breitschwerdt, McKenzie, & Völk 1993). The basic result is that the rates of reconnection (and thus of the formation of “Parker bubbles” leaving the Galaxy by their buoyancy and allowing the generation of the disk magnetic field) and the rates of extension of this field into the Galactic halo by the pressure forces of the wind are roughly equal. Thus, the two effects occur with about equal probability. For the cluster galaxies this means that magnetic energy can be generated on the large scale of the wind at the expense of the thermal and nonthermal enthalpies produced in the starburst. The geometry of the field should roughly correspond to straight field lines out to meridional distances $s$, of the order of the starburst (SB) radius, $R_{\text{galSB}} \sim 1$ kpc in the protogalactic disk, and to spherically diverging field lines beyond that. The slow rotation of the system should then lead to an azimuthal field component, decreasing with the wind distance $\propto 1/s$, which dominates at large distances over the radial component. However, in contrast to the familiar situation in the solar wind equatorial plane, the axis of rotation is parallel rather than perpendicular to the flow at the base of the wind, and thus the dominance of the azimuthal field component is by no means as drastic as in the case of a stellar wind (Fig. 3). The wind becomes supersonic at about the same critical distance, $s_{\text{crit}} \sim R_{\text{galSB}}$. Far beyond this critical point the mass velocity $u(s)$ becomes constant and the density falls off $\propto s^{-2}$.

3.1. Mean Magnetic Field

Choosing a present average baryon density $n_b(z = 0) = 3 \times 10^{-7}$ cm$^{-3}$, i.e., assuming most of the baryonic matter to be in the form of intergalactic gas, the mean density at the
for the above starburst parameters. Therefore, 

\[ n_{\text{cl}}(z = 2) \approx 27 n_{\text{gal}}(z = 0) \equiv n_{\text{gal}}(z = 2) \]

with a present ICM density \( n_{\text{cl}} \gg 10^{-4} \text{ cm}^{-3} \), we have \( n_{\text{cl}}(z = 0)/n_{\text{cl}}(z = 2) \approx 12 \) as a result of gravitational compression of the ICM gas. With a dominant thermal gas pressure, the corresponding adiabatic pressure increase \( P_{\text{cl}} \approx n_{5/3} \) amounts to \( P_{\text{cl}}(z = 0)/P_{\text{cl}}(z = 2) \approx 63 \); for the following we shall use \( P_{\text{cl}}(z = 0)/P_{\text{cl}}(z = 2) = 10^2 \). The wind termination shock distance \( s_{\text{sh}} \) is then given by \( \rho(r_{\text{sh}}) u^2 \approx p_{\text{cl}}(z = 2) \), where \( \rho(r_{\text{sh}}) \) is the wind mass density upstream of the shock.

To estimate the wind characteristics, we assume a quasi-steady state and a strong starburst for which we may disregard gravity, magnetic forces, and CR pressure gradients in the overall energy balance equation (e.g., Zirakashvili et al. 1996). It reads in this case

\[
\frac{u^2}{2} + \frac{\gamma}{\gamma - 1} \frac{P}{\rho} \approx \frac{\gamma}{\gamma - 1} \frac{P_{\text{base}}}{\rho_{\text{base}}},
\]

where, in addition, \( \rho u^2/2 \ll \gamma P/\gamma - 1 \) is assumed at the base \( s = s_{\text{base}} \) of the wind. The critical point \( s_{\text{crit}} \) is given by \( \rho_{\text{crit}} u_{\text{crit}}^2 = \gamma P_{\text{crit}} \). Approximately \( u_{\text{crit}} \approx u_{\text{sh}}/2 \), where \( u_{\text{sh}} \) is the asymptotic wind speed. Beyond the critical point at \( s_{\text{crit}} \approx R_{\text{gal}}^3 \), the wind achieves spherical symmetry, so that from mass conservation

\[
\left( \frac{s_{\text{sh}}}{R_{\text{gal}}^3} \right)^2 \approx \frac{\rho_{\text{crit}} u_{\text{crit}}}{\rho_{\text{sh}} u_{\text{sh}}}.
\]

If the ICM pressure is small compared to the base pressure, then we can assume that the wind is highly supersonic at the shock distance, which implies \( s_{\text{sh}} \approx u_{\text{sh}} \). This should be true for M82-like objects (although they should have a considerably larger scale \( R_{\text{gal}} \sim 1 \text{ kpc} \) that have \( P_{\text{cal}}/kB \sim 10^7 \text{ K cm}^{-3} \). In this case we can assume the wind pressure to evolve adiabatically to lowest order, so that

\[
P_{\text{crit}} \approx \left( \frac{P_{\text{crit}}}{p_{\text{base}}} \right)^{5/3}.
\]

As a result, taking into account that in a flow dominated by the thermal gas the adiabatic index \( \gamma \) is equal to 5/3,

\[
\frac{s_{\text{sh}}}{R_{\text{gal}}^3} \approx \left\{ \frac{4 \gamma}{\gamma + 1} \right\}^{1/(\gamma - 1)} \left( \frac{1}{2(\gamma - 1)} \right)^{1/2}
\]

\[
\times \left( \frac{p_{\text{base}}}{p_{\text{cl}}} \right)^{1/2} \approx 1.27 \left( \frac{p_{\text{base}}}{p_{\text{cl}}} \right)^{1/2} \approx 400
\]

for the above starburst parameters. Therefore,

\[
\frac{s_{\text{sh}}}{d_{\text{gal}}(0)/(1 + z)} \approx 400 \text{ kpc}
\]

\[2 \text{ Mpc}/3 = 0.6.\]

The wind bubble containing the shock-heated wind gas will have a radius still exceeding \( s_{\text{sh}} \). Beyond the bubble, part of the external gas will be shocked by the rapidly expanding bubble gas. This shock-heated gas will exchange energy with the cold ambient gas by heat conduction and instabilities. To some extent such exchanges will also take place with the bubble gas.

Even though the volume of at least initially unmagnetized ICM gas may be large enough so that the ICM gas mass exceeds the mass associated with galaxies by a factor of a few (as observed), it may therefore be that some wind bubbles touch (see Fig. 4). Thus, we should consider whether the magnetic fields of the bubbles can reconnect with each other to produce field lines that pervade the entire cluster. Let us assume that the fastest rate of reconnection proceeds with a speed between 1% and 10% of the Alfvén speed \( V_A \), to be specific, with \( V_A/50 \) (Parker 1992). Then, the present-day reconnection time across a termination shock scale is

\[
t_{\text{rec}} \approx \frac{s_{\text{sh}}}{V_A/50} \approx 9 \times 10^{10} \text{ yr}
\]

\[
\times \left\{ \left( \frac{s_{\text{sh}}}{400 \text{ kpc}} \right) \left( \frac{B}{10^6 \text{ G}} \right)^{-1} \left( \frac{n}{10^{-2}} \right)^{1/2} \right\},
\]

greater than a Hubble time, even for a present-day ICM magnetic field as high as \( 10^{-6} \text{ G} \). Therefore, many bubble fields might not yet be reconnected, and much of the field structure could well remain topologically disconnected until today.

The field strength \( B_{\text{gal}}(z = 2) \) in the early wind bubbles should be of the order of

\[
B_{\text{gal}}(z = 2) \approx 4 B_{\text{gal}} R_{\text{gal}}^3 s_{\text{sh}} / r_{\text{sh}} \sim 10^{-2} B_{\text{gal}} \sim 10^{-8} \text{ G}
\]

or somewhat larger if the field in the bubble increases in the decelerating postshock flow. The subsequent and still ongoing overall cluster contraction/accretion compresses the field to lowest order isotropically \( \propto l^2 \), with the scale factor

\[
l \approx [n_{\text{gal}}(0)/n_{\text{gal}}(z)]^{1/3} / (1 + z),
\]

where \( n_{\text{gal}}(0) \sim 10^{-3} \text{ to } 10^{-4} \text{ cm}^{-3} \) and \( z = 2 \). For a present mean baryon number density \( n_{\text{gal}}(0) \sim 3 \times 10^{-7} \text{ cm}^{-3} \), we obtain \( l \sim 2.3 \to 5 \).

From these estimates, we obtain for the present-day ICM field \( B_{\text{gal}}(z = 0)/B_{\text{gal}}(z = 2) \approx 5 \to 25 \). Therefore, the present-day ICM magnetic field should have a mean strength of the order of \( 10^{-7} \text{ G} \), from 1 \( \mu \text{G} \) “primordial” seed fields, and should be randomly directed on an intergalactic scale. Although smaller by about 1 order of magnitude than estimated from Faraday rotation measurements, such fields need not necessarily be unrealistic, considering that observations might emphasize regions of high magnetic fields. Indeed, the simplest inverse Compton interpretation of the extreme-ultraviolet (EUV) excess and the excess X-ray flux in the Coma Cluster requires such low field strengths (Fusco-Femiano et al. 1999). On the other hand, the increase of the field in the galactic wind bubbles beyond their postshock value might be more than a factor of unity, as assumed above.

An additional possibility is that the “initial” fields for such starburst galaxies might be an order of magnitude stronger than assumed. Apart from a fast dynamo whose strength could be directly proportional to the star formation rate (Parker 1992), we could invoke a systematic field amplification through the commencing galactic outflow that “combs” the field outward. It might occur on very short timescales of about \( 10^7 \text{ yr} \). Empirically, this field amplification is suggested by the statistical time independence of the radio synchrotron-to-far-infrared emission ratio in starburst galaxies (Lisenfeld, Völk, & Xu 1996), which can hardly be understood otherwise than through a
FIG. 4.—Cartoon of the large-scale magnetic field topology in a cluster. The magnetic fields have been originally generated in the (rotating) gas-rich galaxies and are then drawn out by strong galactic winds. The fields are frozen into an ensemble of randomly oriented bubbles created by the winds from early starbursts. For demonstration purposes, less than 10% of all the bubbles expected are shown. Because of reconnection in their interstellar media, the present-day galaxies are no longer dynamically connected to the bubbles. However, magnetic reconnection is rather ineffective in the ICM at large. Therefore, only some of the bubbles will be magnetically connected to their neighbors. Other bubbles just contain hot gas and closed magnetic field loops. The bubbles are surrounded by less magnetized intracluster gas that contains much of the cluster mass. However, they exchange energy by thermal conduction and potentially by instabilities. Cooling flows are not considered in the figure but are possible and, in fact, likely to occur. The configuration is continuously perturbed by the infall of single-field galaxies and the accretion of subclusters that lead to shear amplification and distortion of the simple idealized structures shown, as well as to a high level of magnetic fluctuations.

field that increases almost simultaneously in strength with the star formation rate.

A final argument is that the large-scale shear deformations induced by the later accretion of large subclusters may amplify the field even further. Thus, we cannot exclude \( \mu G \) fields; the force balance certainly allows them.

3.2. Field Evolution and Structure

The wind bubbles and the associated magnetic fields should at some stage decouple from the galaxies they emanated from, simply by magnetic reconnection, which is fastest near the galaxies: the Alfvén velocity is approximately independent of the meridional distance \( s \) in the wind, whereas the distance between oppositely directed field lines that emanate from the galaxy is obviously smaller the smaller \( s \) is. Thus, after the termination of the starburst, the magnetized bubbles and the stellar component of the remaining early-type galaxies should acquire independent identities and their dynamics should decouple.

The topologically disconnected structure of the mean magnetic field in the cluster also has some bearing on the evolution of magnetic field strengths during the development of cooling flows toward the cluster center (Fabian 1994). Instead of building up global magnetic pressure gradients and tension forces, such a subsonic and sub-Alfvénic flow allows optimal internal segregation of high- and low-field regions on galaxy-galaxy separation scales. Thus, we should expect that the field strength toward the cluster center increases by less than isotropic compression, \( B \propto n^{2/3} \), even though at the compressed spatial scales reconnection will be more effective. The two-thirds law should hold only for the overall cluster gas compression discussed earlier.

A question of direct importance for the interpretation of Faraday rotation measurements is the scale of reversal changes of these fields. Field reversals are a natural consequence of the suggested field structure, given the field pattern in the interstellar media of the starburst galaxies. If the Milky Way can serve as a guide, then this pattern is determined by the 100 pc scale of the Parker instability (Parker 1966). From the radius \( r_{\text{gal}} \) to distances of \( \sim r_{\text{sh}} \), this scale projects like the ratio \( r_{\text{sh}}/r_{\text{gal}} \). With the use of the above estimates, this implies a field reversal scale \( \sim 40 \) kpc in clusters, rather well in line with observational estimates that indicate reversal scales of 10–100 kpc (e.g., Kronberg 1994; Clarke, Kronberg, & Böhringer 1999).

3.3. Magnetic Field Fluctuations

From the foregoing arguments there is hardly any need for a contemporary "turbulent ICM dynamo." However,
the ongoing accretion will perturb this mean intracluster field randomly in space and time, maintaining a turbulent magnetic fluctuation field that develops smaller and smaller spatial scales. As a result of the topology of the mean field, the largest turbulent scale is given by the distance between galaxies. The accretion will probably span the range from single-field galaxies falling into the cluster to accreting massive subclusters. As long as this accretion process remains important, one has to expect that the cluster rings with it. At the largest scale the relative magnetic fluctuation level should approach unity (see § 2.3).

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