The Magnetic Fields of the Universe and Their Origin

Stirling A. Colgate & Hui Li

Los Alamos National Lab, T-6, MS B288, Los Alamos, NM 87545

Abstract. Recent rotation measure observations of a dozen or so galaxy clusters have revealed a surprisingly large amount of magnetic fields, whose estimated energy and flux are, on average, $\sim 10^{58}$ ergs and $\sim 10^{41}$ G cm$^2$, respectively. These quantities are so much larger than any coherent sums of individual galaxies within the cluster that an efficient galactic dynamo is required. We associate these fields with single AGNs within the cluster and therefore with all galaxies during their AGN phase. Only the central, massive black hole (BH) has the necessary binding energy, $\sim 10^{61}$ ergs. Only the accretion disk during the BH formation has the winding number, $\sim 10^{11}$ turns, necessary to make the gain and magnetic flux. We present a model of the BH accretion disk dynamo that might create these magnetic fields, where the helicity of the $\alpha - \Omega$ dynamo is driven by star-disk collisions. The back reaction of the saturated dynamo forms a force-free field helix that carries the energy and flux of the dynamo and redistributes them within the clusters.

1. Introduction

The problem of understanding the origin of the large scale galactic magnetic fields has been with us for over forty years. There have been many papers and reviews on the galactic and extragalactic magnetic fields (see Moffatt 1978; Parker 1979; Krause and Radler 1980; Ruzmaikin et al. 1988; Wielebinski & Krause 1993; Beck et al. 1996; Zweibel & Heiles 1997; Kulsrud 1999), and observational reviews (see Miley 1980; Bridle & Perley 1984; Krönberg 1994), including the observations themselves (e.g. Perley et al. 1984; Taylor et al. 1990; Taylor & Perley 1993; Eilek et al. 1984).

Recent rapid progress in observational work on galaxy clusters has revealed a surprising result. Intracluster medium (ICM) appears to be definitely magnetized, and in many cases, perhaps are highly magnetized as convincingly argued by Eilek et al. (2000). Figure 1 presents one such example in Hydra A Cluster as shown by the rotation measure ($R_m$) map made by Taylor & Perley (1993). We will show in this article that the implied magnetic energy and flux estimated from extensive $R_m$ maps of a dozen or so galaxy clusters are so exceedingly large that the conventional galactic dynamo models may prove to be inadequate. We argue that a new source of energy and a different form of the galactic dynamo are required.

As the rotation measure observations of galaxy clusters are relatively new and some of them are (yet) unpublished by the observation teams, we will first
explain some of the observation results in detail, then discuss their physical implications at length. In the second half of the article, we will propose a new paradigm related to AGN accretion disks and describe some of our recent efforts in understanding a sequence of physical processes revolving around the origin of cluster magnetic fields.

2. Galactic and Extragalactic Magnetic Fields

Faraday rotation measures, $R_m$, are shown to be consistent with six other physical interpretations of magnetic fields in ours and nearby galaxies (star light polarization, interstellar Zeeman splitting, synchrotron emission, synchrotron polarization, and inferred by x-ray emission and cosmic ray isotropy and pressure) (see Krönberg 1994 for a review), thus establishing $R_m$ as a reliable measure of galactic and extra galactic magnetic fields. Because of the existence of many self-illuminating as well as background sources, usually AGN, and the increasing sensitivity of radio detection, $R_m$ has become the recognized measure of extragalactic magnetic fields (Krönberg 1994; Taylor et al. 1994; Ge & Owen 1994; Krause & Beck 1998).

2.1. Magnetic Flux and Energy in Galaxy Clusters

Recently, high quality $R_m$ maps of self-illuminating sources of galaxy clusters where the distances are known have become available (for example, Taylor & Perley 1993; Eilek et al. 2000). An important quantity that has received less discussion in these papers is the magnitude of the magnetic flux and energy.

Figure 1 shows the $R_m$ map of the region illuminated by Hydra A in the cluster (courtesy of Taylor & Perley 1993). The largest single region of highest field in this map has approximately the following properties: the size $L \simeq 50$ kpc and $B \simeq 33 \mu$ G, derived on the basis that the field is patchy and is tangled on a 4 kpc scale. This leads to a startling estimates of flux, $F \approx BL^2 \simeq 8 \times 10^4 \mu$ G $kpc^2$, and energy, $W = (B^2/8\pi)L^3 \simeq 4 \times 10^{59}$ ergs, assuming that the tangled field is only confined to the 50 kpc region. If this is extended to the whole cluster which is $\sim 500$ kpc, then the implied flux and energy are correspondingly larger by a factor of 100 and $10^3$, respectively. A similar conclusion can be reached when a larger sample of $R_m$ of galaxy clusters are analyzed using the data presented in Eilek et al. (2000). In Table 1, we have reproduced part of table given in Eilek et al. (2000) and added two columns where the approximate flux and energy are calculated assuming that the fields are partially tangled or in loops.

Furthermore, the estimated values of fluxes and energies are most likely to be the minimum of the actual magnetic fields existing in the galaxy clusters. Faraday rotation depends upon the component of the field strength along the line of sight, $B_\parallel$, the distance along the line of sight, $Z_o$, and electron density, $n_e$. Estimates of $n_e$ can be made from the x-ray emission measurements of the clusters with a typical accuracy of $\sim 20\%$, and it varies by factors of 2 to 4 over the region of the source, but otherwise is nearly uniform, and clumping is small (Taylor et al. 1994). If the field is folded in any fashion so that regions of oppositely directed field are in the line of sight, then the observed $R_m$ will be
Magnetic fields in the Universe

Table 1. A list of cluster core parameters and their estimated magnetic fluxes and energies. Mean magnetic field is taken to be $\sim \sqrt{3} \times \langle B_\parallel \rangle$. Data in the first three columns are taken from Eilek et al. (2000).

| Source   | Size (kpc) | $\langle B_\parallel \rangle$ (µG) | $\langle B^2 L^3/8\pi \rangle$ (10$^{58}$ ergs) | $\langle B L^2 \rangle$ (10$^{41}$ G cm$^2$) |
|----------|------------|-----------------------------------|---------------------------------------------|---------------------------------------------|
| A 400    | 100        | 2.9                               | 3                                           | 5                                           |
| A 1795   | 7          | 18                                | 0.03                                        | 0.17                                        |
| A 2052   | 8          | 17                                | 0.05                                        | 0.17                                        |
| A 2029   | 10         | 1                                 | 0.0003                                      | 0.02                                        |
| A 2199   | 30         | 15                                | 2                                           | 0.3                                         |
| A 2634   | 140        | 1.9                               | 30                                          | 7                                           |
| A 4059   | 10         | 69                                | 0.15                                        | 1                                           |
| Cyg A    | 70         | 15                                | 25                                          | 1.5                                         |
| Hydra A  | 50         | 33                                | 40                                          | 15                                          |
| Virgo A  | 3          | 35                                | 0.01                                        | 0.05                                        |

smaller than that if the same field lines were straightened out into one direction. In other words $R_m$ is a minimum measure of $B_\parallel$.

To put the above numbers in perspective, for a typical galaxy like ours, e.g., with 1 kpc thickness, 3 kpc Homberg radius, and a field of $\sim 3$µ G, the magnetic flux and energy are roughly 10$^{38}$ G cm$^2$ and 4 $\times$ 10$^{52}$ ergs, respectively. One observes that the flux and energy given in Table 1 range from close to the Hydra A limit to no more than 10$^2$ times that of a typical galaxy.

The magnitude of the implied fluxes and energies are so large, $\times 10^3$ and $\times 10^6$ respectively, compared to these quantities within standard galaxies that their origin requires a new source of energy and a different form of the dynamo than previous galactic models. These minimum energies are sometimes even larger than the baryonic binding energy of galaxies ($\sim 2 \times 10^{58}$ ergs). The extremely large fluxes also seem out of reach via amplification by ordinary galaxy rotations in a Hubble time.

Next, we discuss the difficulty with using turbulence to create these nearly uniform, highly correlated and coherent regions of $R_m$ as seen in Figure 1. We then discuss the still greater difficulty of creating the total magnetic energy of the cluster based upon a turbulence dynamo model.

2.2. Turbulent versus Coherent Fields

It has been suggested by a number of people (Eilek 1999; DeYoung 1980; Ruzmaikin et al. 1989; Goldman & Rephaeli 1991; Jaffe 1980) that the entire cluster is uniformly turbulent due to Rayleigh Taylor instabilities during matter in-fall into the cluster, and that this turbulence drives the cluster dynamo creating the fields. The problem with this interpretation is the total magnetic energy, the magnitude of the turbulence, the strength of the fields, the apparent correlation of $R_m$ maps with single AGN structures, and finally the limited number of rotations of the cluster in a Hubble age.
Because of the small rotation rate of the typical cluster, $\sim 100 \text{ km s}^{-1}$, the available rotation energy is small, $\sim 10^{-2}$ of the cluster binding energy; which has a thermal velocity of $\sim 10^3 \text{ km s}^{-1}$. So applying the turbulent model to Hydra A implies a magnetic energy $10^3$ greater than the rotational energy. Therefore the dynamo must be of the $\alpha^2$ type where fields are generated on the small scale, yet as Taylor et al. (1994) point out, the fields of Hydra A and A1795 reverse on the different sides of the core, requiring coherence on scales of 100 kpc. Since this reversal is correlated with the structure of the source, and since the energy generated at the small scale is small compared to the turbulence input and the turbulent input should be small compared to the binding energy (DeYoung 1992), we believe that all these factors point to random, localized sources of magnetic energy of size $> 10^{60}$ ergs. This is probably too demanding for turbulence.

Furthermore, it will be difficult to produce large scale coherent $R_m$ regions, which have been observed in Hydra A (Figure 1, northern region) and several other galaxy clusters (Eilek et al. 2000). This is because in a turbulent plasma, the emission, the $R_m$, and the degree of polarization should all be statistically symmetric. Despite the unlikelihood of all these factors conspiring to create both a pattern and a nearly uniform $R_m$, one observes in many $R_m$ maps of AGN, mostly in clusters, a distinct match in the $R_m$ pattern with the jet like pattern of emission. Particularly the sign of the average $R_m$ in several cases reverses across a symmetry plane through the core of the AGN (Taylor & Perley 1993). The size of the regions of uniform $R_m$ correlates strikingly with the size of the jet as a function of distance from the nucleus. We interpret this correlation as due to the source of the field being the AGN jet as opposed to a turbulent $\alpha - \Omega$ dynamo in the cluster as a whole.

### 2.3. Average Field Structure

Using serendipitous polarized background sources, therefore random lines of sight through random clusters, Clark & Krönberg’s (1999) have made $\sim 80$ $R_m$ measurements. Their observations have produced a boundary of the typical cluster in $R_m$ such that the average field was $\sim 3 \mu \text{G}$ out to a radius of $R_{\text{cluster}} \sim 300$ kpc. The magnetic flux and energy, $10^4 \mu \text{G kpc}^2$ and $10^{60}$ ergs, are then similar to the largest structure already discussed in Hydra A. If each galaxy of a typical cluster with $\sim 50$ large galaxies contributes a high field region during its AGN phase, then the probability of intersecting such a region of area that is $\sim 1\%$ of the cluster is roughly $\sim 5 \times 10^{-3}$ so that in 100 lines of sight, the probability of intersecting a Hydra-like region of an AGN in a cluster is $\sim 50\%$. This is not inconsistent with the variability they observed. Finally we note that the large degree of polarization observed $\sim 50\%$ in these sources indicates that the rotation source and emission source cannot be in the same location (Burn 1966; Taylor 1991), otherwise polarized emission from various depths in the source would undergo different degrees of rotation and hence emerge depolarized. Therefore in any model the Faraday screen and the emission source must be related and even congruent in order that the screen and hence $R_m$ be correlated with the core of the AGN.
2.4. Black Hole Accretion Disk as the Engine

Purely based on the energetics, the accretion disk around supermassive black holes in AGNs offers an attractive site for the production of magnetic fields. The accessible binding energy of the black hole is \( \sim 10^8 M_\odot c^2 \sim 10^{61} \) ergs and the winding number of the disk forming the BH of nearly every galaxy is \( N_w \sim 5 \times 10^{10} \) at \( 10 R_g \), where \( R_g \) is the BH horizon (\( \sim 1 \)AU). Using the canonical numbers thought to apply to AGN disks, the BH dynamo flux can be \( F_{\text{BH dyn}} \approx B_{\text{BH dyn}} \pi R_{\text{BH dyn}}^2 N_w \approx 10^{43} \) G cm\(^2\), where we have used \( B_{\text{BH dyn}} \approx 10^4 \) G at \( L_{\text{AGN}} \sim 10^{46} \) ergs s\(^{-1}\) and \( R_{\text{BH dyn}} \approx 10 R_g \approx 10^{14} \) cm. Both the flux and energy from this simple analysis are \( \sim 10 \) times the maximum observed values. No other source of energy is likely to be sufficient by many orders of magnitude. Therefore it is much more reasonable to assume that every AGN, both within and external to clusters, produces the magnetic energy and flux that we observe in this extreme case from the binding energy released in the accretion disk forming the central BH. This implies that every galaxy contains a BH where \( \sim 90\% - 95\% \) of the accessible binding energy is transformed into magnetic energy during its AGN phase by an accretion disk dynamo. On the average this flux and energy is distributed throughout the universe as force-free fields and only a small fraction \( 5\% - 10\% \) of the magnetic energy is dissipated in the form of the AGN spectra, thus explaining the problem of the missing AGN luminosity (Richstone 1998; Krolik 1999). In this picture a larger fraction of the magnetic energy is dissipated where the brightest AGNs are seen in galaxy clusters, because only in the clusters is a sufficient gas density retained by the gravity of the cluster such that this density confines the field increasing the fraction of the magnetic energy that is dissipated. For most galaxies external to dense clusters a small fraction of this magnetic energy is dissipated as the AGN radiation, a small fraction remains in the galaxy, and the bulk of the magnetic energy and flux is distributed in the walls and voids of the universe.

3. Astrophysical Requirements and Progress with a Model

The sequence of phenomena that can explain this astonishing extragalactic magnetic flux and energy must start with an accretion disk forming a massive central galactic BH. This in turn presumes an answer to an equally enigmatic question, namely the formation of these massive galactic BHs themselves (Begelman et al. 1989; Rees 1999). By focusing on the transport of angular momentum we believe that the flat rotation curve mass distribution can be explained as a plausible result of any non-linear collapse of an initial gaseous baryonic density fluctuation by hierarchical tidal torquing (Newman & Wasserman 1999). The BH forms from this mass distribution when the Rossby vortex torque mechanism supersedes tidal torquing and an accretion disk forms. All this mass then collapses to a BH. The flat rotation curve, \( M \propto R \), results in \( \Sigma \propto R^{-1} \). When this thickness reaches \( \Sigma \approx 100 \) to 1000 g cm\(^{-2}\), heat is confined for several revolutions, and the Rossby vortex instability initiates at \( M_{\text{disk}} \sim 10^7 \) to \( 10^8 M_\odot \). Finally the dynamo produced fields then supersede the previous torque mechanisms.
3.1. The Rossby Vortex Torque Mechanism

We have predicted and demonstrated analytically and numerically how a new instability in Keplerian flow, the Rossby vortex instability, can grow (Lovelace et al. 1999; Li et al. 2000a; Li et al. 2000b). The production of vortices is shown in Figure 2. This instability produces torque and thus transports angular momentum within an accretion disk by purely hydrodynamically means via the interaction of large, two-dimensional, co-rotating Rossby vortices. The enhanced transport of angular momentum by co-rotating vortices is recognized in rotational atmospheric flows (Staley & Gall 1979) and in laboratory measurements of the Ranque-Hilsch tube (Hilsch 1946; Fröhlingdorf & Unger 1999, Colgate & Buchler 1999).

3.2. The Dynamo, Star-Disk Collisions, and Helicity

A coherent dynamo can form in a Keplerian accretion disk because of the large azimuthal velocity shear, provided that there exists a robust source of non-axisymmetric helicity. Classically turbulence has been invoked to explain this helicity using the mean field dynamo theory, but we know of no way to create this degree of turbulence, with vertical motions, hydrodynamically in an accretion disk, because hydrodynamic turbulence alone is damped in an accretion disk (Balbus & Hawley 1998). The magnetic instability of Balbus & Hawley will lead to turbulence, but the magnitude of the turbulence is orders of magnitude too small compared to the Keplerian stress. Instead we have identified a new, robust source of helicity driven by star-disk collisions by a small mass fraction $\sim 10^{-3} - 10^{-4}$ of pre galaxy-formation stars. The Keplerian shear and a star-disk collision with the twist producing helicity is shown in Fig. 3. We have demonstrated by laboratory flow visualization experiments of how plumes, driven in a rotating frame, counter rotate relative to the frame (Beckley & Colgate 1998; Beckley et al. 2000) and thus produce a robust and coherent helicity where flux is always added in the same direction and where the driving force is large compared to the Keplerian stress in the disk.

We have simulated the positive, exponential gain of both the quadrupole and dipole poloidal field of such a dynamo with a vector potential code in 3-D, cylindrical coordinates, where the velocity field simulates both the Keplerian rotation and star collision-produced plumes. We have observed a growth rate of $\sim 10\%$ per revolution, two plumes per two revolutions, $R_{\text{plume}} = 1/3R_{\text{disk}}$, and with a magnetic Reynolds number, $R_{\text{ey},\Omega,B} = 100$ (Pariev, Colgate & Finn 2000).

3.3. The Saturation of the Dynamo and the Formation of the Helix

With positive gain and large winding number, the dynamo will saturate regardless of how small the seed field is. Since the helicity does not depend on turbulence, it will not be subject to turbulent $\alpha$-quenching at the small scale (Vainstein & Cattanio 1992; Vainshtein & Rosner 1991). Furthermore since the stars maintain virial velocity, their velocity is supersonic relative to the disk and the resulting shock stress is large. At the back reaction limit, the field grows until the torque of the field affects the Keplerian motion, and the accessible BH binding energy is converted into magnetic energy. The progressive loss of this flux is a force-free helical, Poynting magnetic flux, which we identify as the collimated
AGN jets. We have investigated the field topology of these twisted helical flux surfaces by integrating the Grad-Shafranov equations for a force-free axisymmetric field with a Keplerian distribution of winding number (Li et al. 2000c) as shown in Fig. 4. Since the field decreases as $B_{\text{helix}} \propto 1/R$, the pressure, at large radius as the helix extends to Mpcs, becomes of the order of the IGM and the outer boundary of the helix is self collimating (Lynden-Bell 1996). The energy carried by this helix, at a mean radius near the BH, $R_{\text{dyn}} \simeq 10R_{\text{BH}}$ is the accessible energy of accretion or $\dot{M}_{\text{BH}}c^2/10 = (B_{\text{helix}}^2/8\pi)(100\pi R_{\text{BH}}^2)$ or $B_{\text{helix}} \simeq 10^4$ G, $I = 5R_{\text{helix}}B_{\text{helix}} = 5 \times 10^{18}$ amperes, and $V_{\text{potential}} = 10^{20}$ volts and $I \times V_{\text{potential}} = 10^{39}$ watts = 10$^{46}$ ergs s$^{-1}$. General relativity inside the innermost stable orbit will add additional energy (Blandford & Znajek 1977; Livio et al. 1999).

3.4. $J_\parallel$ Reconnection and Acceleration

The distribution of this flux in the universe occurs by partial tearing mode reconnection producing the minimum energy Taylor state (Taylor 1986). The total flux is conserved, but a fraction of the energy is dissipated in the tearing mode, $J_\parallel$ reconnection. The resulting $E_\parallel$ acceleration of the current carriers produces the emission that we associate with the AGN.

Acknowledgments. We are indebted to Richard Lovelace, Howard Beckley, Vladimir Pariev, John Finn, Mike Warren, Dave Westpfahl, Van Romero, Ragnar Ferrel, and Warner Miller for direct contributions to this project and to very many more who have contributed in discussions, criticisms and encouragements. HL acknowledges the support of an Oppenheimer Fellowship. This research is supported by the DOE, under contract W-7405-ENG-36.

References

Balbus, S.A., & Hawley, J.F. 1998, Rev. Mod. Phys., 70, 1
Beck, R. et al. 1996, ARAA, 34, 155
Beckley, H.F. & Colgate, S.A. 1998, APS, DFD., Abst. 5253
Beckley, H.F. et al. 2000, Phys. Fluids, to be submitted
Begelman, M.C. et al. 1989, Theory of Accretion Disks, ed. F Meyer, W Duschl, J. Frank, and E Meyer-Hofmeister, NATO series C, Kluwer Pub., 290, p373, ibid p387
Blandford, R.D. & Znajek, R.L. 1977, MNRAS, 179, 433
Bridle, A.H. & Perley, R.A. 1984, ARAA, 22, 319
Burn, B.F. 1966, MNRAS, 133, 67
Clark, T., Krönberg, P.P. & Böhringer, H. 1999, preprint
Colgate, S.A. & Buchler, R.J. 1999, 14th Florida Workshop in Nonlinear Astronomy, ed. R. Buchler and H. Kantrup, Gainesville, FL, Proc. of NY Acad. Sci.
DeYoung, D.S. 1980, ApJ, 241, 81
DeYoung, D.S. 1992, ApJ, 386, 464
Eilek, J.A. et al. 1984, ApJ, 278, 37
Eilek, J.A. 1999, Magnetic fields in Clusters: Theory vs. Observation, Ringberg
workshop, Germany, MPE-Report
Eilek, J.A. et al. 2000, ApJ, to be submitted
Fröhlingsdorf, W. & Unger, H. 1999, Int. Jour. of Heat and Mass Transfer, 42,
415
Ge, J-P. & Owen, F.N. 1994, AJ, 108, 1523
Goldman, I. & Rephaeli, Y. 1991, ApJ, 380, 344
Hilsch, R. 1946, Die Expansion von Gasen im Zentrifugalfeld als Kältprozess,
Zeitung für Naturforschung, 1, 208; and 1947, Rev. Sci. Instr. 18, 108
Jaffe, W. 1980, ApJ, 241, 925
Krause, F. & Beck, R. 1998, A&A, 335, 789
Krause, F. & Radler, K-H. 1980, Mean Field Electrodynamics and Dynamo
Theory, Berlin: Akademie-Verlag, Oxford, Pergamon
Krolik, J.H. 1998, Active Galactic Nuclei, Princeton: Princeton Univ. Press
Kröner, P.P. 1994, Prog. Phys., 57, 325
Kulsrud, R.M. 1999, ARAA, 37, 37
Li, H. et al. 2000a, ApJ, in press
Li, H. et al. 2000b, ApJ, to be submitted
Li, H. et al. 2000c, ApJL, to be submitted
Livio, M. et al. 1999, ApJ, 512, 100
Lovelace, R.V.E. et al. 1999, ApJ, 513, 805
Lynden-Bell, D. 1996, MNRAS, 279, 389
Miley, G.K. 1980, ARAA, 18, 165
Moffatt, H.K. 1978, Magnetic Field Generation in Conducting Fluids, Cambridge Univ. Press
Newman, W.I. & Wasserman, I. 1999, ApJ, 354, 411
Pariev, V., Colgate, S.A. & Finn, J.M. 2000, ApJ, to be submitted
Parker, E.N. 1979, Cosmic Magnetic Fields: Their origin and Their Activity,
Oxford: Claredon
Perley, R.A. et al. 1984, ApJS, 54, 291
Rees, M.J. 1999, astro-ph/9912346
Richstone, D. 1998, Nature, 395, 14
Ruzmaikin, A.A. et al. 1989, MNRAS, 241, 1
Ruzmaikin, A.A. et al. 1998, Magnetic Fields in Galaxies, Astrophy. and Space
Sci. Lib., Kluwer, Dordrecht
Staley, D. O. & Gall, R. L. 1979, J. Atmos. Sci., 36, #6, 973
Taylor, G.B. et al. 1990, ApJ, 360, 41
Taylor, G.B. 1991, Ph.D. thesis, UCLA
Taylor, G.B. & Perley, R.A. 1993, ApJ, 416, 554
Taylor, G.B. et al. 1994, AJ, 107, 1942
Taylor, J.B. 1986, Rev. of Modern Phys., 58, 741
Vainshtein, S.I. & Rosner, R. 1991, ApJ, 376, 199
Vainshtein, L.I. & Cattaneo, F. 1992, ApJ, 393, 165
Wielebinski, R. & Krause, F. 1993, Astron Astro. Rev., 4, 449
Zweibel, E.G. & Heiles, C. 1997, Nature, 385, 131
This figure "figures.png" is available in "png" format from:

http://arxiv.org/ps/astro-ph/0001418v1