On the AGN origin of $\mu$G Magnetic Fields in the Intracluster Medium

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Evidence for Cluster Magnetic Fields: Radio Halos and Relics

over 50 now known $\rightarrow$ cluster mergers

WSRT @ 90 cm

Feretti & Giovannini 1998
Rotation Measure Maps of Cluster Radio Sources

Figure 2  The RM distribution in Cygnus A based on multifrequency, multiconfiguration VLA observations. The resolution is 0.35\arcsec (Dreher, Carilli & Perley 1987). The colorbar indicates the range in RMs from $-3400$ to $+4300$ rad m$^{-2}$. Note the undulations in RM on scales of 10–30 kpc. Contours are overlaid from a 5 GHz total intensity image. The RM was solved for by fitting for the change in polarization angle with frequency on a pixel-by-pixel basis (see Figure 4).
RM versus radius

- Sample of 16 radio halo clusters
- Measured RM due to background and embedded radio sources
- All exhibit magnetic fields out to edge of X-ray emission $\sim 1$ Mpc

Clarke, Kronberg & Boehringer (2001)
Measuring Cluster Magnetic Fields

• Synchrotron emission
  – Equipartition assumption between B and n_{rel} yields B from radio surface brightness (Burbidge 1959)

• Faraday rotation
  \[ RM = \frac{\chi_{pol}}{\chi^2} = \frac{n_e}{cm^{-3}} \left( \frac{B}{\mu G} \right) \left( \frac{d\ell}{kp c} \right) \text{rad/m}^2 \]
  – B depends on assumed field correlation length

• Inverse Compton X-ray emission
  – If same rel. electrons responsible for radio synchrotron and IC x-rays, then
  \[ \frac{L_{synch}}{L_{IC}} \propto \frac{U_{mag}}{U_{rad}} \Rightarrow B = 1.7(1 + z)^2 \left( \frac{S_r \nu_r}{S_x \nu_x} \right)^{0.5} \mu G \]
Summary of Observations

### TABLE 1  Cluster magnetic fields

<table>
<thead>
<tr>
<th>Method</th>
<th>Strength $\mu$G</th>
<th>Model parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchrotron halos</td>
<td>0.4–1</td>
<td>Minimum energy, $k = \eta = 1$, $\nu_{\text{low}} = 10$ MHz, $\nu_{\text{high}} = 10$ GHz</td>
</tr>
<tr>
<td>Faraday rotation (embedded)</td>
<td>3–40</td>
<td>Cell size = 10 kpc</td>
</tr>
<tr>
<td>Faraday rotation (background)</td>
<td>1–10</td>
<td>Cell size = 10 kpc</td>
</tr>
<tr>
<td>Inverse Compton</td>
<td>0.2–1</td>
<td>$\alpha = -1$, $\nu_{\text{radio}} \sim 18000$, $\nu_{\text{xray}} \sim 5000$</td>
</tr>
<tr>
<td>Cold fronts</td>
<td>1–10</td>
<td>Amplification factor $\sim 3$</td>
</tr>
<tr>
<td>GZK</td>
<td>$&gt;0.3$</td>
<td>AGN = site of origin for EeV CRs</td>
</tr>
</tbody>
</table>

Carilli & Taylor 2002
Possible Origins for Cluster B-fields

- Magnetized jets and winds from galaxies and AGN
- Ram-pressure stripping of cluster galaxy interstellar fields
- Compression of intergalactic fields
- Biermann battery seed fields generated during structure formation, amplified by cluster turbulence
Our Hypothesis

- A single injection of B-fields by an AGN is sufficient to magnetize the entire cluster to observed levels if
  - injection is early enough
  - major mergers induce cluster-wide turbulence
Cluster Assembly

- Cluster mass assembled through mergers of sub-clusters between $z=2-1$
- Drives strong turbulence

![Cluster images with redshifts](image1)

![Graph showing Virial mass and KE density over time](image2)
What we did

• Performed cosmological AMR MHD simulation of galaxy cluster formation using newly developed ENZO-MHD code
  – Inject magnetic jet at z=3 for 36 Myr and then evolve ICM to the present epoch
  – See what happens to injected field
  – Maintain uniform 11 kpc resolution throughout cluster-forming region wherever B>5 x 10^{-8} G
  – \(\rightarrow\) effectively a 600³ uniform grid tracking cluster-forming region within cosmological simulation
Cosmological AMR MHD in ENZO

Collins et al. (2010)

\[
\frac{\partial \rho}{\partial t} + \frac{1}{a} \nabla \cdot (\rho v) = 0
\]  
(1)

\[
\frac{\partial \rho v}{\partial t} + \frac{1}{a} \nabla \cdot \left( \rho vv + \tilde{p} - \frac{BB}{a} \right) = -\frac{\dot{a}}{a} \rho v - \frac{1}{a} \rho \nabla \Phi
\]  
(2)

\[
\frac{\partial E}{\partial t} + \frac{1}{a} \nabla \cdot \left[ v(\tilde{p} + E) - \frac{1}{a} B(B \cdot v) \right]
= -\frac{\dot{a}}{a} \left( \rho v^2 + \frac{2}{\gamma - 1} p + \frac{B^2}{2a} \right) - \frac{\rho}{a} v \cdot \nabla \Phi
\]  
(3)

\[
\frac{\partial B}{\partial t} - \frac{1}{a} \nabla \times (v \times B) = 0
\]  
(4)

with the equation of state

\[
E = \frac{1}{2} \rho v^2 + \frac{p}{\gamma - 1} + \frac{1}{2} B^2
\]

\[
\tilde{p} = p + \frac{1}{2} B^2.
\]

**Numerical methods**
- Structured AMR (Berger & Collela)
- TVD MHD patch solver (Li & Li)
- CT field evolution (Gardner & Stone)
- Divergence free reconstruction (Balsara)
- Dual energy formulation (Bryan et al.)
Magnetic Jet Injection

- Li et al. (2006) magnetic tower model

**Poloidal flux function**

\[ \Psi(r, z) = r^2 \exp(-r^2 - z^2), \]

**Poloidal B-field**

\[ B_{inj, r} = -\frac{1}{r} \frac{\partial \Psi}{\partial z} = 2zr \exp(-r^2 - z^2), \]

\[ B_{inj, z} = \frac{1}{r} \frac{\partial \Psi}{\partial r} = 2(1 - r^2) \exp(-r^2 - z^2). \]

**Toroidal B-field**

\[ B_{inj, \phi} = \frac{\alpha \Psi}{r} = \alpha r \exp(-r^2 - z^2), \]

**Scaling parameters:**

- \( B_0 = \) source field normalization
- \( L = \) source region size
- \( \alpha = \) toroidal/poloidal flux ratio

\[ E_{mag} \propto \alpha^2 B_0^2 L^3 \]
AGN injection into $z=3$ protocluster
AGN injection into $z=3$ protocluster

diagram with density maps $\rho_b$ and $U_B$ over time from $z=1$ to $z=0$
Evolution of Energies

36 Myr injection phase
major merger
turbulent amplification by “small-scale dynamo”
Power spectra in 5.5 Mpc cube

\[ \varepsilon(k) \text{[erg cm}^{-2}\text{kpc}^{-1}] \]

- **Saturation**
- **Exponential growth**

\[ k^{5/3} \]
\[ k^{3/2} \]
Diffusion of $B$
Synthetic FRM Map

- +/- 500 rad/m\(^2\) max
- highest in cluster core, as observed
- banding due to field reversals, as observed
- filamentary structure on 40 kpc scale (4\(\Delta x\))

3 Mpc
Dependence on injection energy

- Varying magnetic energy injected over ~ 3 orders of magnitude at $z=3$ results in less than 1 order of magnitude magnetic energy at $z=0$
- B-fields still cluster filling

Xu et al. (2010)
Evolution of magnetic energy

Xu et al. (2010)
Radial distribution of $|B_{\text{rms}}|$
Dependence on injection redshift

- Magnetic fields injected before cluster mass buildup are dispersed and amplified by cluster turbulence
- Magnetic fields injected too late remain confined to radio lobes

Xu et al. (2010)
Evolution of magnetic energy

![Graph showing the evolution of magnetic energy over time and redshift. The graph plots magnetic energy in $10^{30}$ ergs against time in $10^9$ years, with redshift on the top axis.]
Radial distribution of $|B_{\text{rms}}|$
Conclusions

• A single powerful radio jet at high $z$ can magnetize entire ICM to levels observed
  – Weakly sensitive on injected energy

• Timing of AGN injection important:
  – Early: cluster-wide B
  – Late: isolated bubbles

• Turbulent amplification and diffusion are the fundamental processes