Magnetic Fields in Clusters of Galaxies

Dongsu Ryu (UNIST, Korea)

Faraday rotation measure

Hydra North

(Ryu et al 2008)

(Vogt & Ensslin 2005)
The large-scale structure of the universe → the cosmic web

observed and simulated galaxy distributions

filaments

clusters

void regions

where most matters reside

simulated matter distribution

November 2, 2017
CHEA Collaboration Meeting
UNIST, Korea
Clusters of galaxies → aggregates of galaxies, which are the largest known gravitationally bound objects to have arisen thus far in the process of cosmic structure formation.

Hubble space telescope image ← mostly star light

the intracluster medium (ICM) ← the superheated plasma with $T \sim \text{a few to several keV}$, presented in clusters of galaxies

MACSJ0717

optical (Hubble, white) ← hot gas

X-ray (Chandra, blue) ← cosmic rays

radio (VLA, red) ←
ICMs are dynamical:
- turbulent flow motions
- large-scale flow motions
- magnetic fields
- cosmic-rays
- shock waves
Magnetic fields in galaxy clusters appear in observations

(Clarke et al 2004)

Faraday rotation measure
(Vogt & Ensslin 2005)

Hydra North

CIZA J2242.8+5301
Sausage relic

(van Weeren et al 2010)

Giant & Thinner radio relic so far

(Brown & Rudnick 2011)

Coma cluster
Relic halo

GMRT 610 MHz radio image

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Table 3. Magnetic field estimates derived from various methods in the clusters Coma and A3667.

<table>
<thead>
<tr>
<th>Name</th>
<th>Method</th>
<th>Field strength ($\mu$G)</th>
<th>Location</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>Coma</td>
<td>Equipartition</td>
<td>0.45</td>
<td>radio halo</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>Equipartition</td>
<td>0.55</td>
<td>radio relic</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>Faraday Rotation</td>
<td>7</td>
<td>cluster center</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Faraday Rotation</td>
<td>0.2</td>
<td>cluster center (large scale)</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Inverse Compton</td>
<td>0.2</td>
<td>cluster average</td>
<td>114</td>
</tr>
<tr>
<td>A3667</td>
<td>Equipartition</td>
<td>1.5–2.5</td>
<td>NW relic</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>Inverse Compton</td>
<td>$\geq 0.4$</td>
<td>cluster average</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>Faraday Rotation</td>
<td>1–2</td>
<td>cluster center</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>Faraday Rotation</td>
<td>3–5</td>
<td>NW relic</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>Cold front</td>
<td>10</td>
<td>along the cold fronts</td>
<td>153</td>
</tr>
</tbody>
</table>

Column 2 gives the method used to estimate the field strength, Column 3 the value of the magnetic field in $\mu$G, Column 4 describes the location in the cluster at which this estimation is made, Column 5 gives the reference.

modeling of synchrotron of the Sausage relic $\Rightarrow B_1 \sim 2 - 2.5$ G \cite{Kang2015}
modeling of synchrotron of the Toothbrush relic $\Rightarrow B_1 \sim 1 - 1.5$ G \cite{Kang2017}
Fluid quantities in ICM outskirts

- Size of clusters: \( L_{\text{cluster}} \sim \text{a few Mpc} \sim 10^{25} \text{ cm} \)
- Baryon number density: \( n \sim 10^{-3} \text{ cm} \)
- Flow velocity: \( v \sim \text{several } \times 100 \text{ km/s} \)
- Gas temperature: \( T \sim 10^8 \text{ K (8.6 keV)} \rightarrow c_s \sim 1500 \text{ km/s} \)
- Magnetic fields: \( B \sim \text{a few } \times \mu \text{G} \rightarrow c_A \sim 100 \text{ km/s} \)

→ Flows are subsonic (\( M_s \sim 0.5 \)) but super-Alfvenic (\( M_A > 1 \))

- Gas thermal energy: \( E_{\text{thermal}} \sim \text{a few } \times 10^{-11} \text{ erg/cm}^3 \)
- Gas kinetic energy: \( E_{\text{kinetic}} \sim \text{a few } \times 10^{-12} \text{ erg/cm}^3 \)
- Magnetic energy: \( E_{\text{magnetic}} \sim \text{a few } \times 10^{-13} \text{ erg/cm}^3 \)
- Cosmic-ray energy: \( E_{CR} < \sim \text{a few } \times 10^{-13} \text{ erg/cm}^3 (E_{\text{thermal}} / 100) \)

→ Plasma beta is high with \( \beta \sim 50 - 100 \)

\[
\beta \equiv \frac{P_{\text{thermal}}}{P_{\text{magnetic}}} \equiv \frac{2E_{\text{thermal}}}{3E_{\text{magnetic}}}
\]
Turbulence dynamo model for magnetic fields in clusters of galaxies

large-scale structure formation
- gravitational collapse, mergers, & flow motions

shocks in the LSS of the Univ
- shock dissipation
  - stretching and compression
  - generation of vorticity

development into turbulence
- small-scale or turbulent dynamo
  - seed fields

amplification of magnetic fields

(e.g., Ryu et al 2008)
Observation of shocks in clusters: X-ray

The Bullet Cluster

$M_x \approx 3.0$
(no associated radio relic)
(Markevitch 2006)

$M_x \approx 2.5$
(Shimwell et al. 2015)

Cluster A665

$M_x = 3 \pm 0.6$
(no associated radio relic)
(Dasadalia et al. 2016)
Observation of shocks in clusters: radio relics

van Weeren et al. + Ryu 2017
Shock waves induced during the formation of the large-scale structure of the universe

Shock waves in a simulated clusters of galaxies

strong accretion shocks with $M > 10$ (green)

weak inreaccluster shocks with $M < 4$ (orange)

(Vazza et al + Ryu)
Vorticity generated at cosmological shocks

- directly at interacting and curved shocks

\[ \omega_{cs} \sim \frac{(\rho_2 - \rho_1)^2}{\rho_2 \rho_1} \frac{\vec{U} \times \vec{n}}{R} \]

\( \rho_1 \) preshock density
\( \rho_2 \) postshock density
\( \vec{U} \) preshock flow speed
\( \vec{n} \) unit normal to shock surf.
\( R \) curvature radius of surf.

- by the baroclinic term

\[ \omega_{bc} = \frac{1}{\rho_2} \nabla \rho \times \nabla p \]

Magnitude of vorticity or enstrophy (e) enhanced by stretching and compression increases during the development of turbulence

\[ \frac{\partial \epsilon}{\partial t} = F_{adv} + F_{stretch} + F_{comp} + F_{baroc} + F_{mag} + F_{diss} \]

(Porter, Jones, Ryu 2015)
Theory of turbulence

Kolmogorov's theory for incompressible hydrodynamic turbulence: it is based on the notion that that large eddies can feed energy to the smaller eddies and these in turn feed still smaller eddies, resulting in a cascade of energy from the largest eddies to the smallest ones.

On dimensional grounds, the only way of writing $\varepsilon$ (energy transfer rate) in terms of $\nu$ (velocity) and $l$ (scale) is

$$\varepsilon \sim \frac{\nu^2}{t} \sim \frac{\nu^3}{l} \sim \text{constant}$$

$$\nu \sim l^{1/3}$$

$$p_{k} \sim k^{-5/3}$$

The spectrum of Kolmogorov turbulence

The spectrum of the turbulent energy cascade from large to small scales
Turbulence in high resolution simulations of galaxy clusters

$\text{curl}(v)$ in the plane through the cluster center

(Miniati 2013)

in simulations, turbulence exists in all over the clusters!
Turbulence energy of in the ICM assuming that turbulence is contained in vortical motions

\[ M_{\text{turb}} \sim 1 \] (transonic turbulence)

in filaments

\[ M_{\text{turb}} < \sim 1 \] (subsonic turbulence)

\[ \frac{E_{\text{turb}}}{E_{\text{therm}}} \sim 0.1 \sim 0.3 \]

inside and outskirts of clusters

(Ryu et al 2008)
Evidences for turbulence in clusters

Observations of turbulence in clusters are mostly around core regions!

At the core of the Perseus cluster, the estimated turbulence velocity $\sim 165$ km/s, (while the expected value $\sim 500$ km/s)

(Hitomi Collaboration 2016)
Patchy Faraday rotation measure (RM) in clusters observed with radio galaxies

Murgia et al. (2004)

- RM in Abell 119 for comparison with simulation
- Turbulent cluster magnetic fields with power-low slope $n=2$ give a good fit (Kolmogorov $n=11/3$)

An evidence for turbulence in cluster outskirts?
Turbulence in astrophysical environments with magnetic fields

Fluid and magnetic fields interact with each other
- fluid $\rightarrow$ drags magnetic field
- magnetic field $\rightarrow$ exerts tension and pressure
  $\Rightarrow$ fluid and magnetic field moves together ("frozen")
  with large magnetic Reynolds number

\[ \frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla)\vec{v} + \frac{1}{\rho} \nabla p = \frac{1}{4\pi \rho} (\nabla \times \vec{B}) \times \vec{B} \]

\[ \frac{\partial \vec{B}}{\partial t} = -\nabla \times (\vec{B} \times \vec{v}) \]

Turbulence + magnetic field
$\Rightarrow$ Magnetohydrodynamic turbulence
Origin of magnetic fields in clusters

- generation of seed fields

- amplification of seed fields by turbulent flow motions
Seed magnetic fields in the large-scale structure (LSS) of the universe

Suggestions include:
- generation in the early universe (e.g., see Widrow, Ryu et al 2012 for review)
  e.g.) during the electroweak phase transition (t~10^{-12}sec)
  during the quark-hadron transition (t~10^{-5}sec)
  → uncertain but maybe challenging (?)
- generation before the formation of the LSS of the universe
  through plasma physical processes (e.g., see Ryu et al 2012 for review)
  e.g.) Biermann battery or Weibel Instability at shocks
  (Kulsrud, Cen, Ostriker, & Ryu 1997) (Medvedev & Loeb 1999)
  instabilities, thermal fluctuations, photo-ionization and etc ...
  → weak (~ 10^{-20} G) and some at small scales, yet most promising (?)
- astrophysical processes
  e.g.) magnetic fields from the first stars
  → maybe not the first magnetic field

Origin of seeds for cosmic magnetic fields is uncertain!
Small-scale dynamo of MHD turbulence with weak initial field

\( \frac{E_{\text{mag}}}{E_{\text{kin}}} \sim \frac{1}{2} \cdot \frac{2}{3} \)

Growth of magnetic energy at saturation

\[ V^2(t) : 256H-B_010^{-4} \]
\[ V^2(t) : 512H-B_010^{-4} \]
\[ V^2(t) : 1024H-B_010^{-4} \]
Evolution of magnetic field power spectrum at early stages

(From J. Cho)
Power spectrum at saturation

(Jo & Ryu, unpublished)
A model for magnetic fields in galaxy clusters

- vorticity generated at shocks and also due to baroclinity
- further enhanced by stretching and compression
- developed into turbulence
- magnetic field produced by turbulence dynamo

The model may reproduce the observed strength of magnetic field!

(Ryu et al 2008)
Large-scale magnetic fields in cluster outskirts?

CIZA J2242.8+5301 (sausage radio relic)

Can Mpc-scale magnetic fields in outskirts, “if real”, be explained by turbulence dynamo?

(van Weeren et al 2010)
The growth time of magnetic fields in turbulence dynamo

It takes $t \sim \text{several} \times t_{\text{eddy}}$ to reach $E_{\text{mag}} \sim 1/10 E_{\text{kin}}$

In clusters, if turbulence is driven mainly by major mergers,

$L_{\text{injection}} \sim 500 \text{ kpc}$ (clump size)

$v_{\text{turb}} \sim 500 \text{ km/s}$

$\Rightarrow t_{\text{eddy}} \sim 1 \text{ Gyrs} \sim 1/10 t_{\text{age}}$

or $t_{\text{age}} \sim 1/10 t_{\text{eddy}}$

($t_{\text{age}}$ the age of the universe)

There seems to be enough time for the growth of $B$!
The scale of magnetic fields in turbulence dynamo

Power spectrum at saturation (Porter, Jones, & Ryu, 2015)

At $t \sim 10 t_{\text{eddy}}$
the peak of $P_{\text{mag}}(k)$ is $\sim 1/3 L_{\text{injection}}$
the peak of $kP_{\text{mag}}(k)$ is $\sim 1/10 L_{\text{injection}}$

If $L_{\text{injection}} \sim 500 \text{ kpc}$,
the peak of "$kP_{\text{mag}}(k)$" (the peak scale of magnetic energy) $\sim 50 \text{ kpc}$, too small?
In clusters of galaxies, the turbulence is driven “sporadically”, mostly by “mergers”.

The medium is “stratified”, i.e., high density at cores and low density at outskirts.

Intracluster media are highly “stratified”, i.e., high density at cores and low density at outskirts.

Turbulence energy dissipation rate in a cluster formed in a simulation for the formation of the large-scale structure of the universe.

(Coma cluster)
Simulations of turbulence “sporadically” driven in “staratified” clusters (Roh, Ha & Ryu, preliminary)

Clusters of $T = 10^8$ K ($c_s = 1,500$ km/s) described the beta model with $\beta = 1$ and $r_c = 300$ kpc in a box of $L_{\text{size}} = 4$ Mpc

turbulence of $M_{\text{turb}} \sim \frac{1}{2}$, driven for 4 times (that is, forcing on for $\Delta t = 0.1 \ t_{\text{age}}$ and off for $\Delta t = 0.15 \ t_{\text{age}}$) during the age of the universe, $t_{\text{age}}$, with the peak of forcing at $L_{\text{injection}} = 500$ kpc

Amplification of B up to $E_{\text{mag}} \sim E_{\text{kin}}/10$ would be OK.

How about the scale of $B$?
The power spectra of velocity and magnetic field at $t = 5$ ($\sim t_{\text{age}}$)

- Uniform medium, constant forcing
- Uniform medium, sporadic forcing
- Stratified medium, constant forcing
- Stratified medium, sporadic forcing
Power spectra of turbulence in stratified medium with sporadic forcing

- $P_{\text{kin}}(k)$ shows large-scale (scales up to the box size) powers
- $P_{\text{mag}}(k)$ has a broad peak over $\frac{1}{2} k_{\text{injection}} - 2 k_{\text{injection}}$
- $kP_{\text{mag}}(k)$ has a peak at $\sim 2k_{\text{injection}}$

or if $L_{\text{injection}} = 500 \text{ kpc}$, the peak scale of magnetic energy $\sim 200 - 300 \text{ kpc}$
Slice images through the cluster center at $t = 4.5$ Mpc

- less concentration of $E_{\text{kin}}$ and $E_{\text{mag}}$ than $\rho$
- higher flow activities at outskirts

$\Rightarrow$ can this reproduce the observed polarization properties of radio relics?
Shocks and magnetic fields

B on the top of $\text{div}(v)$ ($|B|$ on the log scale)

zoomed regions showing perpendicular shocks ($B$ and shock normal are perpendicular)
Summary

- Magnetic field is ubiquitous in the large-scale structure of the universe including in clusters of galaxies.

- Magnetic fields of ~ a few μG in cluster outskirts could be explained by turbulence dynamo.

- The existence Mpc-scale magnetic fields in cluster outskirts need to be established in observation.

- Explaining large-scale magnetic fields of ~ Mpc scale, if they exist, would remain challenging in the picture of turbulence dynamo.
Thank you!