Turbulence and Magnetic Field in High-\(\beta\) Plasma of Intracluster Medium

Coma cluster of galaxies

Dongsu Ryu
UNIST (Ulsan National Institute of Science and Technology, Korea)
KASI (Korea Astronomy and Space Science Institute, Korea)

Hyesung Kang (PNU, Korea), T. W. Jones (Minnesota, USA), others

October 27, 2016
Colloquium at NAOC
Beijing, China
Earth’s magnetic field

strength $\sim 0.25 - 0.65$ G
($1 \text{ G} = 10^{-4} \text{ T}$)

Computer simulation

Magnetosphere - shields harmful radiations from space

Reversal of magnetic field

Interval $\sim 0.1$ to 50 million years

The last event - the Brunhes-Matuyama reversal of $\sim 0.78$ million years ago

History of reversal
Solar and Galactic magnetic field

Sun’s photosphere $\sim 1\, \text{G}$
sunspots $\sim 1\, \text{kG}$

interstellar medium $\sim$ several $\mu\text{G}$
molecular clouds $\sim \text{mG}$
The large-scale structure of the universe

observation of galaxies

clusters of galaxies

filaments

void regions

→ the cosmic web

simulation of matter distribution

October 27, 2016

Colloquium at NAOC

Beijing, China
Clusters of galaxies: \( B \sim \text{a few } \mu \text{G} \)

Filaments of galaxies: \( B \sim 10 \text{ nG} \)

Void regions: \( B > \sim 10^{-16} \text{ G} \)

Distribution of cosmological shocks

\( Mpc = 3.26 \times 10^6 \) light-years

\( h = \frac{\text{Hubble constant}}{100 \text{ km/s}} = \sim 0.7 \)
Magnetic field is ubiquitous in the Universe.

Star
- Magnetar: $\sim 10^{13} - 10^{15} \text{ G}$
- Neutron star: $\sim 10^{11} - 10^{13} \text{ G}$
- White dwarf: $\sim 10^{6} \text{ G}$
- Ap/Bp star: $\sim 10^{3} \text{ G}$
- Normal star: $\sim 1 \text{ G}$

Molecular cloud: $\sim 10^{-3} \text{ G}$

Interstellar medium: $\sim \text{ several x10}^{-6} \text{ G}$

Cluster of galaxies: $\sim \text{ a few x 10}^{-6} \text{ G}$

Filament of galaxies: $\sim 10^{-10} \text{ G (?)}$

Void: $\sim 10^{-16} \text{ G (?)}$

Early universe: $\sim 10^{-20} \text{ G (?)}$

Planck mass monopole: $\sim 10^{55} \text{ G}$
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

optical (Hubble, white)

X-ray (Chandra, blue) ← hot gas

radio (VLA, red) ← cosmic rays

The intracluster medium (ICM)

the superheated plasma with $T \sim$ a few to several keV, presented in clusters of galaxies
ICMs are dynamical:
- large-scale flow motion
- shocks
- turbulence
- magnetic fields
- cosmic-rays
Some Evidence for turbulence in clusters

- pressure fluctuations in Coma (Schuecker et al 2004)
  \[ \Delta P/P \sim 0.1 \]
  \[ n \sim 1/3 \rightarrow 7/3 \ (P_k \sim k^{-n}) \rightarrow \text{consistent to Kolmogorov} \]

- X-ray surface brightness fluctuations in Coma (Churazov et al 2011)
  \[ \Delta r/r \sim 0.1 \]
  \[ n \sim 2 \rightarrow \text{steeper than Kolmogorov (shock-dominated ?)} \]

- line broadening limit in A1835 (Sanders et al 2010)
  \[ \Delta v < 274 \ \text{km/sec} \rightarrow \frac{E_{\text{turb}}}{E_{\text{tot}}} \sim 0.1 \]

- patchy Faraday rotation distributions in clusters (Murgia et al 2004)
  \[ n \sim 0 \text{ for B} \rightarrow \text{broken power-law?} \]

- and etc ...
Turbulence in Coma cluster

\[ \rho \sim k^{-5/3} \]  
(power spectrum of density)

Mach number of turbulence in ICMs, \( M_{\text{turb}} \), less than 1, 
\( \sim 0.5 \) if incompressible mode dominates
Magnetic fields in galaxy clusters appears in observations

- GIZA J2242.8+5301 Sausage relic
- Coma cluster Relic halo
- Hydra North
- Faraday rotation measure

(van Weeren et al 2010)
(Shea Brown)
(Vogt & Ensslin 2005)
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 (μG)</th>
<th>Location</th>
<th>Reference</th>
</tr>
</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>≥ 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 μG, Column 4 describes the location in the cluster at which this estimation is made, Column 5 gives the reference.

(Govoni & Feretti 2004)
Fluid quantities in the ICM

- size of clusters: $L_{\text{size}} \sim \text{a few Mpc} \sim 10^{20} \text{ km}$
- density of baryonic matter: $n \sim 10^{-2} \text{ cm}^{-3}$
- flow velocity: $\nu \sim \text{several} \times 10^2 \text{ km/s}$
- gas temperature: $T \sim 10^8 \text{ K} \rightarrow c_s \sim 10^3 \text{ km/s}$
- magnetic fields: $B \sim \text{a few } \mu \text{G} \rightarrow c_A \sim 10^2 \text{ km/s}$

$\rightarrow$ flows are subsonic ($M_s \sim 0.5$) and super-Alfvenic ($M_A > 1$)

- gas thermal energy: $E_{\text{thermal}} \sim 10^{-10} \text{ erg/cm}^3$
- gas kinetic energy: $E_{\text{kinetic}} \sim 10^{-11} \text{ erg/cm}^3$
- cosmic-ray energy: $E_{\text{cosmic-ray}} \sim \text{a few} \times 10^{-12} \text{ erg/cm}^3$
- magnetic energy: $E_{\text{magnetic}} \sim \text{a few} \times 10^{-12} \text{ erg/cm}^3$

$\rightarrow$ plasma beta is high $\beta \sim 100$

$$\beta \equiv \frac{P_{\text{gas}}}{P_{\text{magnetic}}}$$
A model for turbulence and 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
- amplification of magnetic fields

(Ryu et al 2008)
Origin of turbulence and magnetic fields in clusters

- generation of turbulence

    structure formation ?

    AGN outflows ?

    wakes of galaxies ?

    instabilities ?

    etc ...

- generation of seed fields

    primordial ?

    or astrophysical ?

- amplification of seed fields by turbulent flow motions
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)
(Dasadia et al. 2016)
Observation of shocks in clusters: radio relics

van Weeren et al. + Ryu 2016
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)

Simulation credits: Vazza, Jones, Gheller, Bruggen, Brunetti & Ryu, on ITASCA at Minnesota Supercomputing Institute (MSI). Visualization credits: 3D renderings (Jones) with Hierarchical Volume Rendering, 'HVR,' developed in the LCSE at the University of Minnesota. Critical support from MSI (D. Porter) and LCSE (M. Knox).

https://www.youtube.com/watch?v=yV3KPz0cPqk
Shocks around a simulated cluster in a 2D slice (in the plane through the center)

\[(6h^{-1}\text{Mpc})^2\]

(Hong, Ryu, Kang, & Cen 2014)

- gas density
- temperature
- shock Mach no.

Structures of shocks in galaxy clusters are complex!

- accretion shock from voids to clusters
- shocks due to mergers of sub-clusters
- infall shock (accretion from WHIM to hot IGM)
Vorticity generated at cosmological shocks

- directly at interacting and curved shocks

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

- by the baroclinic term

\[ \dot{\omega}_{bc} = \frac{1}{\rho^2} \nabla \rho \times \nabla p \]

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

(Porter, Jones, Ryu 2015)
Vorticity in a cluster complex

(Ryu, Kang, Cho, & Das 2008)

October 27, 2016
Colloquium at NAOC
Beijing, China
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 $V$ (velocity) and $l$ (scale) is

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

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

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

dimensional power spectrum of velocity!

The spectrum of Kolmogorov turbulence
Turbulence in high resolution simulations of galaxy clusters

vorticity in the plane through the cluster center

(Miniati 2013)
Solenoidal & compressional components of turbulence

fraction of turbulent kinetic energy flux in compressive component

mostly in solenoidal (incompressible) component

the fraction of compressional component \(< \sim 10\%\)

(Vazza et al + Ryu 2016)
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)

\( E_{\text{turb}}/E_{\text{therm}} \sim 0.1 - 0.3 \) inside and outskirts of clusters

(Ryu et al 2008)
Origin of turbulence and magnetic fields in clusters

- generation of turbulence
  structure formation ?
  AGN outflows ?
  wakes of galaxies ?
  instabilities ?
  etc ...

- generation of seed fields
  primordial ?
  or astrophysical ?

- 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!
Laboratory reproduction of magnetic field generation through the Biermann battery mechanism at shock waves (Kulsrud, Cen, Ostriker, Ryu 1997)

~ $10^{-21}$ G by $t \sim 10^9$ years or $t \sim 1/10 t_{\text{univ-age}}$

theory: predicted the generation of seeds of cosmic magnetic fields at curved intergalactic shock waves

experiment: after scaling, confirmed the generation of $10^{-21}$ G magnetic field in the cosmic scale

(Gregori et al 2012)
Toward magnetic field generation by the Weibel instability at collisionless shocks

theory: requires magnetic fields at astrophysical collisionless shocks
what if a shock forms in collisionless plasma with no or weak magnetic field?

(Huntington et al 2015)

simulation: predicts magnetic field generation by the Weibel instability

experiments: confirms the prediction
Origin of turbulence and magnetic fields in clusters

- generation of turbulence

structure formation ?
AGN outflows ?
wakes of galaxies ?
instabilities ?

etc ...

- generation of seed fields

primordial ?
or astrophysical ?

- amplification of seed fields by turbulent flow motions
Turbulence with magnetic fields

Magnetic fields play an important or crucial role with magnetic field
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

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

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

Turbulence + magnetic field
$\Rightarrow$ Magnetohydrodynamic turbulence

October 27, 2016
Colloquium at NAOC
Beijing, China
Turbulence in astrophysical environments

- Turbulence in the interstellar medium (ISM) with $\beta \sim 1$ (strong regular or background field field) → Goldreich & Sridhar model

- Turbulence in the intracluster medium (ICM) with $\beta >> 1$ (no regular or background field field) → super-Alfvenic turbulence
  magnetic fields are amplified by turbulence from weak seed fields → turbulence dynamo or small-scale dynamo

- Two turbulences should have different properties!
Small-scale dynamo of MHD turbulence with weak initial field

Emag/Ekin ~ 2/3

Growth of magnetic energy at saturation

E_{mag}/E_{kin} \sim 2/3
Evolution of magnetic field power spectrum at early stages

(From Cho)
Power spectrum at saturation
A model for magnetic fields in galaxy clusters

- vorticity generated at shocks and also due to baroclinicity
- turbulence developed
- standard picture of MHD turbulence applied
- magnetic field produced by turbulence dynamo

In galaxy clusters
- $B \sim$ a few $\mu$G
- $L_{\text{int}} \sim$ a few x 10 kpc

(Ryu et al 2008)
Magnetic fields in clusters

energy injection scale: \( L_{\text{inj}} \sim \text{a few } \times 100 \text{ kpc} \)
turbulent flow speed: \( v_{\text{turb}} \sim \text{several } \times 10^2 \text{ km/s} \)

\( \Rightarrow \) eddy turn-over time: \( t_{\text{eddy}} \sim \text{several } \times 10^8 \text{ yrs} \)

- magnetic fields in clusters
  \( <B> \sim \text{a few } \mu \text{G}, \ L_{\text{int}} \sim \text{several } \times 10 \text{ kpc} \)

the integral scale is a length scale of magnetic field, which would be relevant to Faraday rotation measure

\[
L_{\text{int}} = 2\pi \left( \int (E_B / k) dk / \int E_B dk \right)
\]
Large-scale magnetic fields?

CIZA J2242.8+5301 (sausage radio relic)

(magnetic field geometry: large-scale field of ~ 2 Mpc?)
Laboratory reproduction of magnetic field amplification through turbulence (turbulence or small-scale dynamo): TDYNO (Tzeferacos et al + Ryu 2016)

In clusters: several x100 kG

In lab: ~ a few µG

Experimental exploration for the turbulence dynamo origin of magnetic fields in clusters of galaxies
Plasma properties in high $\beta$ plasma in the ICM

size of clusters

\[ L_{\text{size}} \sim \text{a few Mpc} \sim 10^{20} \text{ km} \]

Coulomb mean free path

\[ l_{\text{Coul}} \sim \text{a few kpc} \sim \frac{L_{\text{size}}}{10^3} \]

gyro-radius of thermal protons

\[ r_{\text{gp}} \sim 10^6 \text{ km} \]

gyro-radius of thermal electrons

\[ r_{\text{ge}} \sim 10^3 \text{ km} \]

ion inertial length

\[ \lambda_i \sim 10^4 \text{ km} \]

electron skin depth

\[ \lambda_e \sim 10^2 \text{ km} \]

Debye length

\[ \lambda_D \sim 10 \text{ km} \]

plasma parameter

\[ \Lambda \sim 10^{17} \]

\[ \Lambda \equiv 4\pi n_e \lambda_{\text{Debye}}^3 = 4\pi \left( \frac{k}{4\pi e^2} \right)^{3/2} n_e^{-1/2} T_e^{3/2} \sim \left( \frac{\text{thermal K.E.}}{\text{Coulomb P.E.}} \right)^{3/2} \]

→ plasma is collisionless ($l_{\text{Coul}} \gg r_{\text{gp}}$) and weakly coupled ($\Lambda >> 1$)
Intracluster media (ICMs) of galaxy clusters

- may be treated as fluids on the cluster scale, $L_{\text{size}} > \sim \text{Mpc}$
- host turbulence, which would be hydrodynamic (HD) on largest scales but MHD on smaller scales
- contain shock waves with $M_s \sim$ a few
- below Coulomb collision scale $l_{\text{Coul}} \sim$ a few kpc, plasma effects may enter
- gyro and inertial scales of thermal particles are much smaller than $l_{\text{Coul}}$
- with $\Lambda \gg 1$, they are good plasmas, e.g., carry plasma waves

→ We need to study fluid phenomena as well plasma phenomena to understand ICMs!
Viscosity and resistivity the ICM

**kinetic viscosity**

\[ \nu \sim \nu_{\text{therm}} \frac{l_{p-p}^2}{t_{p-p}} \]

or substantially smaller?

**resistivity**

\[ \eta \sim \frac{(c / \omega_p)^2}{t_{e-p}} \left( \omega_p = \left( \frac{4 \pi n_e e^2}{m_e} \right)^{1/2} \right) \]

much smaller than viscosity?

high magnetic Prandtle number?

\[ P_m = \frac{\nu}{\eta} \sim 10^{20} \text{ or larger?} \]
Turbulence with $B_0 \ll \delta B$ and large $P_m$

- Time evolution of kinetic and magnetic energies

$P_m \gg 1$

$mP_1 = mP$ at saturation
magnetic energy $\gg$ kinetic energy

$E_{\text{kin}}, E_{\text{mag}}$

$P_m = 1$

$V^2(t) : 256H-B_0 10^{-4}$
$V^2(t) : 512H-B_0 10^{-4}$
$V^2(t) : 1024H-B_0 10^{-4}$

$B^2(t) : 256H-B_0 10^{-4}$
$B^2(t) : 512H-B_0 10^{-4}$
$B^2(t) : 1024H-B_0 10^{-4}$
- Power spectrum at saturation

\[ P_m \gg 1 \]

with \( \nu \gg \eta \), \( V_k \ll B_k \)

\[ E_M \sim \text{constant}, \quad E_K \sim k^{-3} \]

in the inertial range
Summary

- Magnetic field is ubiquitous, even in the large-scale structure of the universe.

- Magnetic field of ~ a few $\mu$G of coherence length of ~ several 10 kpc in clusters of galaxies could be explained by turbulence (small-scale) dynamo.

- But there are a number of issues to be further resolved... e.g., mean-free-path ~ a few kpc (size of clusters ~ a few Mpc) plasma effects in collisionless regime? Mpc-scale magnetic field?

...
Thank you!