Turbulence in Clusters of Galaxies

Dongsu Ryu (Chungnam National U, Korea)

Collaborators:
Hyesung Kang (PNU, Korea), Jungyeon Cho (CNU, Korea)
Tom W. Jones, David Porter (Minnesota, USA)
Zhibin Guo, Jahyung Jo, Jae-Min Kwon, Pat Diamond (NFRI, WCI)

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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.

Coma Cluster

in visible (core region) ← star light

in X-ray ← hot gas of $T \sim 8$ keV

The intracluster medium (ICM) → the superheated plasma with $T \sim$ a few keV, presented in clusters of galaxies.
Perseus Cluster

X-ray from hot gas of $T \sim 5$ keV

radio due to non-thermal processes
The large-scale structure of the universe seen in the galaxy distribution

“cosmic web of filaments”

Coma cluster

growth of primordial density perturbations via gravitational instability to form the large scale structure of the universe
Some Evidence for turbulence in clusters

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

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

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

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

- and etc …
XMM images of Coma

analyzed to get the power spectrum of gas density fluctuations

Churazov et al. (2011)
Some Evidence for turbulence in clusters

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

- X-ray surface brightness fluctuations in Coma (Churazov et al 2011)
  $\Delta \rho/\rho \sim 0.1$
  $n \sim 2$ $\rightarrow$ steeper than Kolmorogov (shock-dominated?)

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

- and etc ...
Turbulence in clusters: Faraday rotation

- used RM in Abell 119 for comparison with simulation
- n=2 is a good fit and Kolmogorov (n=11/3) does not reproduce the data

Murgia et al. (2004)
Some Evidence for turbulence in clusters

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- and etc ...

\[ \rightarrow \text{turbulence is subsonic!} \]
Drivers of turbulence in clusters

- formation of large-scale structure: shocks from merger, accretion, ...
- AGN outflows, galactic winds, ...
- MTI, buoyancy instabilities, ...

wide range of injection scales: microscopic scales to ~ 1 Mpc
Overall picture for cosmological shocks

- **large-scale structure formation**
- **gravitational collapse & flow motions**
- **cosmological shocks**
  - shock dissipation
  - the main channel to flow the gravitational energy to the intergalactic medium

- **other sources, such as AGNs of heat, CRs, turbulence and magnetic fields**
- **generation of heat**
- **fresh acc. & re-acc. of CRs**
- **genera. of magnetic fields**
- **generation of vorticity**

- **cascade into turbulence**
- **turbulent amp. of mag. fields**
- **turbulent acceleration of CRs**
Velocity field and shocks in a cluster complex

X-ray

$\rho_{\text{gas}}$

$T$

shocks

$(25 \, h^{-1}\text{Mpc})^2$ 2D slice

Shocks with small Mach number are common and energetically important inside and outskirts of clusters.

in hot gas with $T > 10^7$

(inside and outskirts of clusters)

Kang & Ryu (2011)
Radio relic in CIZA J2242.8+5301

- Shock Mach number: $M \sim 4.5$ (too strong?)
- Strong magnetic field: $B \sim 6$ (very strong!)
- High polarization: $\sim 70\%$ or so $\rightarrow$ uniform B

van Weeren et al (2010)
Sausage Relic, $S_{\nu}(\text{mJy}), n_0=10^{-4}$

- $\xi = 1.0 \times 10^{-5}$
- $R_2 = 3.8 \times 10^{-3}$
- $\psi = 10$

- $M = 4.5$
- $B = 7$
- $\psi = 10$

**Injection only**

- $M = 4.5$
- $B = 3.5$
- $\psi = 10$

**Pre-existing CRs with slope 4.2**

Kang, Ryu, & Jones (in preparation)
Vorticity generated at cosmological shocks

directly at curved shocks

\[ \nabla B = 0 \]

\[ \nabla B \neq 0 \]

different jump of \( B \) (Bernoulli function)

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

by the baroclinic term

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

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

baroclinity

due to entropy variation
induced at shocks

constant \( \rho \)

constant \( \rho \)
Vorticity in a cluster complex

Turbulence in clusters: AMR simulations

Vazza et al (2010)

temperature distribution in a merging cluster
Turbulence energy of in the ICM assuming that all the energy of vortical motions goes to turbulence

\[ \frac{M_{\text{turb}}}{\text{therm}} < 1 \] (subsonic turbulence) inside and outskirts of clusters

\[ \frac{E_{\text{turb}}}{E_{\text{therm}}} \sim 0.1 - 0.2 \] inside and outskirts of clusters

\[ \rightarrow \text{agrees with obs.} \]

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

Turbulence amplifies magnetic fields

\[ \rightarrow \text{magnetohydrodynamic turbulence} \]

in astrophysical environments
Magnetic fields in the intergalactic space

- Clusters of galaxies: $B \sim 10 \text{ nG}$
- Filaments of galaxies: $B \sim 10 \text{ nG}$
- Void regions: $B \sim 10^{-16} \text{ G}$ (?)

143 Mpc = $5 \times 10^8$ yr

Distribution of cosmological shocks

November 16 – 19, 2011  6th Korean Astrophysics Workshop  APCTP, Korea
Clusters of galaxies - magnetic fields
Faraday rotation measure of a few x 100 rad/m²
→ B ~ a few μG (core region)

(Clarke et al 2004)

Hydra North

Vogt & Ensslin (2005)
Origin of magnetic fields in clusters

- turbulence dynamo

- AGN outflows, galactic winds, ...

- microscopic instabilities, such as mirror, fire-hose ...
  (contrIBUTE only to very small-scale fields ?)

- and etc ...
Origin of seeds for cosmic magnetic fields is uncertain. Some suggestions:

1. Generation in the early universe
   - e.g., during the electroweak phase transition ($t \sim 10^{-12}\text{sec}$)?
   - during the quark-hadron transition ($t \sim 10^{-5}\text{sec}$)?

2. Generation before cluster formation
   - e.g., plasma processes such as thermal fluctuations
     or at shocks

3. Magnetic fields from the first stars and active galaxies
   ...

It is difficult to produce strong coherent magnetic fields in the IGM before the formation of the large-scale structure of the universe, but rather it would be reasonable to assume that week, random seed fields were created.

After turbulence amplifies magnetic fields

$$B_0 \ll \delta B \quad \text{in the ICM} \quad \text{(while} \quad B_0 \sim \delta B \quad \text{in the ISM)}$$
Simulation of turbulence dynamo or small scale dynamo (incompressible MHD)

$E_{\text{mag}} \sim \frac{2}{3} E_{\text{kin}}$ at saturation

$t / t_{\text{turn-over}} \sim 1 / \omega$

Growth of coherence length (inverse cascade)
### Resulting magnetic fields and numbers in clusters of galaxies

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>magnetic fields</strong></td>
<td>$B \sim \text{a few } \mu\text{G}$</td>
</tr>
<tr>
<td><strong>density of baryonic matter</strong></td>
<td>$n \sim 10^{-2} \text{ cm}^{-3}$</td>
</tr>
<tr>
<td><strong>flow velocity</strong></td>
<td>$v \sim \text{several } \times 10^{2} \text{ km/s}$</td>
</tr>
<tr>
<td><strong>gas temperature</strong></td>
<td>$T \sim 10^{8} \text{ K}$</td>
</tr>
<tr>
<td><strong>gas thermal energy</strong></td>
<td>$E_{\text{thermal}} \sim 10^{-10} \text{ erg/cm}^{3}$</td>
</tr>
<tr>
<td><strong>gas kinetic energy</strong></td>
<td>$E_{\text{kinetic}} \sim 10^{-11} \text{ erg/cm}^{3}$</td>
</tr>
<tr>
<td><strong>magnetic energy</strong></td>
<td>$E_{\text{magnetic}} \sim 10^{-12} \text{ erg/cm}^{3}$</td>
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</tbody>
</table>

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magnetic fields

← could be produced and maintained mostly by turbulence dynamo but also contributed by feedbacks from galaxies
Why care about turbulence in clusters?

- turbulence transports heat and momentum
  -> controls heat conduction and viscosity

- turbulence accelerates particles
  -> turbulent acceleration of cosmic rays

- turbulence transports entropy, metals, etc

- turbulent pressure contributes to the support of the ICM
  -> its presence influences HSE mass estimates

- and etc...
Diffusions in the ICM

heat conductivity
\[ \chi \sim v_e^{\text{therm}} l_{e-e} \sim \frac{l_{e-e}^2}{t_{e-e}} \]

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

resistivity
\[ \eta \sim \frac{(c / \omega_p)^2}{t_{e-p}} \quad \left( \omega_p = \left(\frac{4\pi n_e e^2}{m_e}\right)^{1/2} \right) \]
Various length scales in the intracluster medium

mean free-path for electron-electron & proton-proton collisions

\[ l_{p-p} \approx l_{e-e} \approx \frac{10^5}{\ln \Lambda} \frac{T^2(K)}{n_e(cm^{-3})} \text{cm} \sim \text{a few kpc} \]

mean free-path for electron-proton relaxation

\[ l_{e-p} \sim l_{p-p} \times \left( \frac{m_p}{m_e} \right)^2 \sim 100 \text{ kpc} \]

gyro-radius of protons

\[ r_{\text{gyro},p} \sim \frac{\sqrt{T(K)}}{B(G)} \text{cm} \sim 10^4 \text{ km} \]

gyro-radius of elections

\[ r_{\text{gyro},e} = r_{\text{gyro},p} \times \frac{m_e}{m_p} \sim 10 \text{ km} \]
- the peak scale of magnetic fields, $k_{\text{peak}}$, grows as turbulence develops.
- it occurs at $L_{\text{peak}} \sim 1/2 L_{\text{inj}}$ at saturation.
Kubo number

\[ \kappa = \frac{\delta B}{B_0} \frac{l_{||}}{l_{\perp}} \]

(Kubo number by direct ave
Kubo number by spectrum.)

\( \kappa > 1 \) (the critical balance does not hold, so the GS description breaks down!)

\( B_0 \ll \delta B \) in the ICM

\( \kappa \sim 1 \) (G-S ?)

k_{peak}

Jo, Kwon, Diamond, Ryu, Cho
(preliminary)
Various length scales in the intracluster medium

peak scale of magnetic field power spectrum

\[ L_{\text{peak}} \sim \text{a few -} 100 \text{ kpc} \]

mean free-path for electron-electron & proton-proton collisions

\[ l_{p-p} \sim l_{e-e} \sim \frac{10^5}{\ln \Lambda \; n_e (\text{cm}^{-3})} T^2 (\text{K}) \text{ cm} \sim \text{a few kpc} \]

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gyro-radius of elections

\[ r_{\text{gyro}, e} = r_{\text{gyro}, p} \times \frac{m_e}{m_p} \sim 10 \text{ km} \]
We need to consider diffusion in different regimes:

\[ \kappa > 1 \quad \& \quad \text{collisional} \quad \text{for} \quad L >\sim 100 \text{ kpc} \]
\[ \kappa \sim 1 \quad \& \quad \text{collisionless} \quad \text{for} \quad L >\sim a \text{ few kpc} \]

and also

\[ \kappa > 1 \quad \& \quad \text{collisionless} \]
\[ \kappa \sim 1 \quad \& \quad \text{collisional} \]

Guo, Diamond, Ryu (preliminary)
Conclusions

- Turbulence in clusters is important and yet to be understood.

- Simulating turbulence in clusters is rather tricky business, both because the physics is not well understood and because the computational requirements are very demanding.

- Good progress has been made, however, in attacking this and improving our understanding of the properties and roles of turbulence in this environment.

- Most importantly, there are a wealth of physics issues, waiting for us to solve them!
Thank you!
Simulations of isothermal compressible MHDs to study turbulence in clusters

- $c_s = 1$, $V_{rms} \sim 0.45$ (so $M_s \sim 0.45$) at saturation subsonic turbulence ($E_{\text{kin}}/E_{\text{therm}} \sim 0.1$)

- initially very weak field with $\beta = 10^6$

- purely solenoidal forcing (and purely compressive forcing)

- ideal MHD, so Pr ~ 1 (and Pr >> 1)

- injection at $L_{\text{inj}} \sim 1/2\ L_{\text{box}}$

- in a periodic box with $L_{\text{box}} = 10$
  sound crossing time ~ 10
  eddy turn-over time ~ 22

- up to $2048^3$ grid zones

Porter, Jones, Ryu, Cho (in preparation)
Power spectrum

$P_K(k)$ for sol. mode

$P_K(k)$ for comp. mode

purely solenoidal forcing  purely compressible forcing

for subsonic ($M_s \sim 0.45$) and high beta ($\beta = 10^6$) turbulence
Simulations of isothermal compressible MHDs
to study turbulence in clusters

- $c_s = 1$, $V_{rms} \sim 0.45$ (so $M_s \sim 0.45$) at saturation
  subsonic turbulence ($E_{\text{kin}}/E_{\text{therm}} \sim 0.1$)

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  (and purely compressive forcing)

- ideal MHD, so $Pr \sim 1$
  (and $Pr >> 1$)

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  sound crossing time $\sim 10$
  eddy turn-over time $\sim 22$

- up to $2048^3$ grid zones

Porter, Jones, Ryu, Cho
(in preparation)
Incompressible MHD turbulence with different magnetic Prandtl number

$P_{\text{mag}}(k)$ at saturation

$P_{\text{vel}}(k)$ at saturation

$k^{-5/3}$

$k^{-4}$
Growth of magnetic energy

\[ \frac{E_{\text{mag}}}{E_{\text{kin}}} \approx \frac{2}{3} \text{ at saturation} \]