Cosmological MHD

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- Observational overview of large scale magnetic fields
- Several examples of numerical modeling of cosmological MHD
Part I: Observations
Galaxy Clusters

MS0735.6+7421

Hydra A
Cluster Accretion Shocks (?)

Bachigi et al. 2006, Science
Beyond Clusters.... (???)

Adapted from: Kim, Kronberg, Giovannini and Venturi, NATURE, 1989

Part II:

Origin of Extra-Galactic Magnetic Fields
Numerical simulations

- Λ cold dark matter cosmology
  \[ \Omega_\Lambda = 0.73, \Omega_{DM} = 0.27, \Omega_{gas} = 0.043, h=0.7, n = 1, \sigma_8 = 0.8 \]
  without/with gas cooling

- computational box: \((100h^{-1} \text{ Mpc})^3\)
  1024^3 cells for gas and gravity, 512^3 DM particles, \(\Delta x = 97.7 \hmpkpc\)

\[ \rho = 1 - 10^4 <\rho> \text{ and higher} \]

Ryu et al. 2005

Baryon Density

Vorticity Generation
Cosmic Energy Flow

Gravity

Stars, galaxies, galaxy clusters, large scale shocks, etc.

Gravity → IGM

IGM

“Feedback”
- Mechanical
- Chemical
- Thermal
- Non-Thermal
- Magnetic

collapse

Black Holes

Radiation
- Kinetic Winds
- Magnetic fields

10^8 M_{sun} → 10^{62} ergs
Part III:

Astrophysical Jet Modeling and Interaction with ICM
global current flow

\[ J_z @ t = 10 \]

toroidal \( B \phi \) from \( I_z \)
(“lobes”)

“flux core: \( \Psi \) & \( I_z \)”
(“helix/jet”)

confinement
(\( B^2 \phi / 8 \pi \sim p_{\text{gas}} \))

(Li et al. 2006, Nakamura, Li, Li 2006, 2007)
Hydra A

Diehl, Li, et al. 2007
Zavala & Taylor 2005
3C273
Differential FRM

Is there current in jets?
Part IV:

Magnetic Fields Injected from SMBHs
Growing “cherries” on cosmic trees... 

$z=2$

20 Mpc/(1+z)

Johnson et al. in preparation
$B = 0.1 \mu G$

$Z = 1.985 \quad t = 9.0 \times 10^6$

Li et al. 2007
Part V: Cosmological MHD Simulation of Cluster formation with Magnetic Fields
AMR MHD Cluster Formation Simulations

$\Lambda$CMD model, $\Omega=1$, $\Omega_\Lambda=0.7$, $\Omega_b=0.04$, $h=0.7$, and box size = 256 Mpc. Root grid is $128^3$, refined by 2 to level 8, simulation is from $z=30$ to $z=0$.

Same simulation with radiative cooling, star formation and star formation feedback, uniform initial magnetic fields of $1e-9$ G in y direction.

Projected logarithmic baryon density, refined to level 2, 4, 6 and 8. Each plot has a resolution of 512x512 zones. Best spatial resolution is 7.8125 kpc/h.
Magnetic Energy Density Evolution

[Graph showing magnetic energy density evolution with scale bars for 256Mpc/h and 4Mpc/h]
SZ Effect: y-parameter
AMR MHD Cluster Formation Simulations

Imagines of cluster center (1Mpc/h)

Gas density

SZ_y

Magnetic energy density

Rotation measurement
AMR MHD Cluster Formation Simulations

\( \Lambda \)CMD model, \( \Omega = 1, \Omega_\Lambda = 0.7, \Omega_b = 0.04, h = 0.7 \), and box size = 256 Mpc/h. Root grid is 128\(^3\), refined by 2 to level 8, simulation is from \( z = 30 \) to \( z = 0 \). No initial magnetic fields

Imagines of projected baryon density of inner 4 Mpc/h at \( z = 0 \), left is from MHD solver and right is from ppm solver
AMR MHD Cluster Formation Simulations

$\Lambda$CDM model, $\Omega=1$, $\Omega_\Lambda=0.7$, $\Omega_b=0.04$, $h=0.7$, and box size = 256 Mpc/h. Root grid is $128^3$, refined by 2 to level 8, simulation is from $z=30$ to $z=0$. No initial magnetic fields

Y parameter of SZ Effect of slice of inner 4 Mpc/h at $z=0$, left is from MHD solver and right is from ppm solver
AMR MHD Cluster Formation Simulations

ΛCMD model, $\Omega = 1, \Omega_{\Lambda} = 0.7, \Omega_{b} = 0.04, h = 0.7$, and box size = 256 Mpc/h. Root grid is $128^3$, refined by 2 to level 8, simulation is from $z=30$ to $z=0$. No initial magnetic fields.

X-ray luminosity of inner 4 Mpc/h at $z=0$, left is from MHD solver and right is from ppm solver.
Some Key Problems

1. **Diffused Radio Emission:** Distribution and strength of cosmic magnetic fields, seeding from first stars, dwarf galaxies, AGN feedbacks, or (turbulent) dynamo.
2. **Differential FRM of jet pc-kpc scale:** is there current?
3. **Clusters as magnetic field laboratories:** Structure formation, AGNs, heating, mixing, etc.
4. **Physical state of IGM:** impact on galaxy formation?
5. **UHECR** transport?
6. Does magnetic energy flow destroy the statistics of **Lyman-alpha forests**?