Simulations with cosmic magnetic fields
ranging from galactic and intergalactic effects to cosmological galaxy formation

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Why magnetic fields?

• Everywhere you can find astrophysical plasma in the Universe. The plasma comes with magnetic fields!
• Basically, magnetic fields connect all scales ranging from the particle scale to the cosmological scale, converting energy among mechanical energy, magnetic energy, and particle/radiation energy.
  – Cosmic-ray acceleration and propagation.
  – Star formation in giant molecular clouds.
  – Turbulence in ISM and IGM.
  – Interaction between ISM and IGM.
  – Stellar and SMBH processes (winds, jets, and explosions).

Question: where and when are the effects of B-fields important? (i.e. generation and amplification/de-amplification problems.)
Zeeman splitting of 21cm line shows that the Damped Lyman Alpha system DLA-3C286 at $z = 0.692$ has $B \sim 84$ microGauss (Wolf et al. 2008).
NGC 6946 B-field vectors.

Pressure distribution of central ICM in Coma cluster (Schuecker et al. 2004).
Ideal MHD

... resistive MHD
... collisionless MHD
... zero viscosity/conductivity

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

It’s critical to know the correct relative geometry and strength between momentum (i.e. velocity) vector and B-field vector!

NRL Plasma Formulary
Simulations codes consist of two parts

1) Dynamical core
   - Precise conservation of mass, momentum, and energy.
   - $\nabla \cdot B = 0.$
   - Invisic ideal MHD solver.

2) Physical parameterization
   - Cooling/heating and other energy terms.
   - Approximate processes over grid-sizes (e.g., chemical reaction, convection).
   - Sub-grid models (formation/death of astrophysical objects, feedback, turbulence, stellar dynamo, etc.)
   - The net effect is dispersion or diffusion, working as source and sink terms.
   - The right sequence in the simulation codes is not well understood for general cases. This part is a common source of numerical instability (Lian et al. 2010).
Case 1: magnetized shock-cloud interaction (~ 8000 AU)

- Athena (Gardiner & Stone, 2005 and 2007).
- No gravity. Smooth hydrostatic cloud mass distribution.
- Multiple orientations and strengths of B-fields for a Mach ~ 10 shock.
- Uniform-grid simulations.
- Cell size ~ 90 AU.
Parallel shocks

(See Harpreet Dhanoa’s Poster for the effects of chemical processes.)
Case 2: ram pressure stripping of galaxies with magnetic fields (~380 kpc)

- Shin & Ruszkowski (in prep.) for MHD runs.
- See Shin & Ruszkowski 2013 for hydro runs.
- See Ruszkowski+ 2012 for simulations of disk-type galaxies.
- Static gravity. + Driven turbulence in the ISM.
  (Non-turbulent ICM.)
- Two orientations of B-fields for an elliptical experiencing ICM ram pressure.
- Minimum cell size ~ 1 kpc with AMR.

Non-magnetized but turbulent ISM.
What do we expect with B-fields and the turbulent ISM?

- Different mixing between ISM and ICM.
- Instability on the boundary grows in different ways.
- Morphology of ram pressure stripping tails.
- B field transportation from galaxies to ICM.
- B field amplification.
- Cosmic-ray transportation and acceleration (due to magnetic field reconnection and shocks; see Butt 2009).

(See Marco Bocchio’s poster about dusts in ram pressure stripping.)
Parallel B-filed in the ICM.

Perpendicular B-filed in the ICM. This loses more ISM.
Parallel B-filed in the ICM.

Perpendicular B-filed in the ICM.

Red : 2 Gyr.
Blue : 4 Gyr.
Black : 6 Gyr.
Case 3: cosmological galaxy formation simulation (~ 200 Mpc/h)

- RAMSES (Teyssier, 2002).
- The AMR method is used inside 200 Mpc/h box, resolving the minimum cell size ~ 0.76 kpc/h in fiducial runs. The run of zoom-in simulations resolves ~ 0.1 kpc/h.
- Shin, Devriendt, Slyz+ in prep.
- Dynamic gravity + cosmological environment.
- Two types of runs: star formation + stellar feedback (under tests and exploration of models) vs. only star formation (done).

Problems that we want to examine include:
- Where and how can we see the fossil records or effects of the primodial B-field?
- How is the large-scale B-field connected to the galactic-scale B-field?
- How do stellar processes change cosmic B-field?
- Can we incorporate resonable sub-grid models which produce acceptable net effects of turbulence dynamo and stellar processes?
The results from two different spatial distributions of primordial B-fields.

- \( B \sim 1.0 \times 10^{-13} \) Gauss at \( z \sim 53 \).

- No stellar processes except for star formation.

- Plots at \( z \sim 0.88 \) for the fiducial run.

- Halo mass vs. average gas density (top) and B-field strength.

**Uniform initial B-field.**

**Gaussian random initial B-field.**

https://docs.google.com/file/d/0B6RRLlKNN-CjdRFdEZDNfdXhEMDQ/edit?usp=sharing
Issues in cosmological galaxy formation simulations

• Our understanding of initial B-field conditions is highly limited. Even we do not know some critical kinetic-scale physics such as a cosmic-ray diffusion rate.

• There is no systematic satisfying picture of B-field generation/amplification processes in stellar systems and their evolution.

• Turbulent dynamo seems essential in this scale. However, the process driving the turbulence is not resolved. (See Dominik Schleicher’s posters.)

• We are exploring several simple models which connect stellar processes (star formation and feedback) to physical parametrization of B-field source/sink terms with coupling to mass/momentum/energy terms.

• The net effect should include back-reaction from small-scales or approximation to large-scales evolved by the correct dynamical core of the codes.

• The Divergence-B = 0 condition restricts the ways of injecting or sinking B-field components in the simulations. (Bias is worse than variance.)