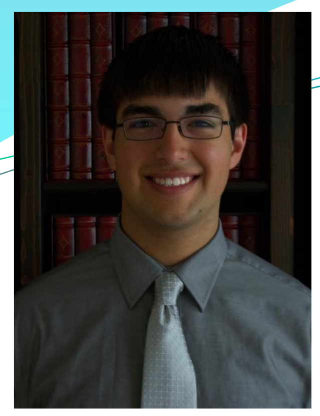
Simulation of Turbulence and Magnetic Field Evolution in Astrophysical Plasmas



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Introduction: Background

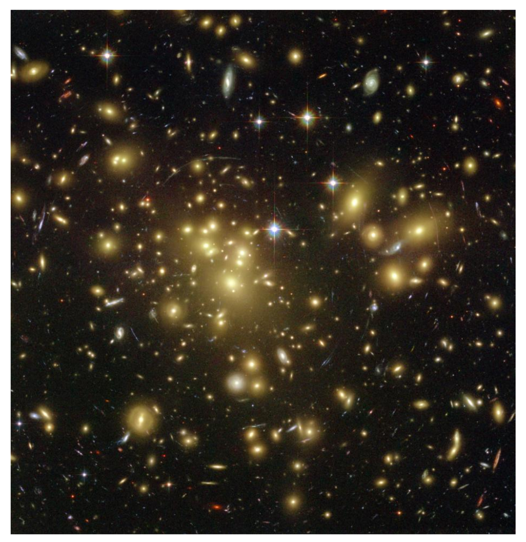


Figure 1. Optical image of galaxy cluster Abell 1689.

Galaxy clusters are the largest gravitationally bound objects in the Universe. A characteristic cluster contains hundreds of galaxies spread over ~3 megaparsecs, or roughly 10^6 light years, and contain over 10^{14} times more mass than the sun. ***Fig. 1*** shows an optical image of a large galaxy cluster. A significant portion of a cluster's mass is contained within the hot, diffuse plasma spread between a cluster's constituent galaxies, called the Intra-cluster medium (ICM). The ICM is dynamic and complex, with turbulence driven by a variety of sources and a vast magnetic field, with strength on the order of a few micro-Gauss, or μG. This magnetic field evolves with the turbulence, and is important in understanding the evolutionary process of galaxy clusters today. They, and the turbulence that drives them, are the source of many cluster phenomena, such as radio halos. These objects are used as a key diagnostic by astronomers to understand the properties and evolutionary process of a given galaxy cluster.

Cosmological Simulations

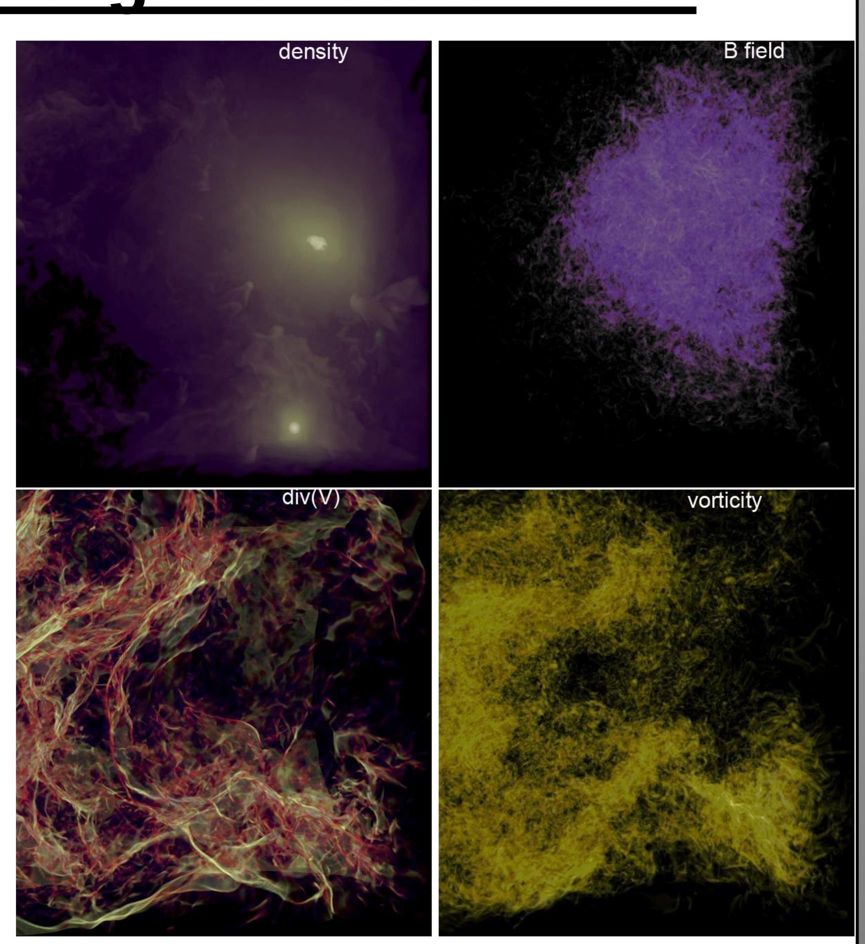


Figure 2. A high resolution simulation of the merger of two galaxy clusters. Shown is a rendering of the density (top left), magnetic field strength (top right), vorticity, or turbulence strength bottom right), and the divergence of the velocity of the plasma, which indicates regions of compression, (bottom left). [Images courtesy of Dr. Tom W. Jones and Dr. Francesco Miniati.]

Cosmological Simulations

Unfortunately, it is not possible to construct one's own galaxy cluster in a laboratory and watch it evolve. Even if it was, one would have to wait around for several billion years for the experiment to finish! Astrophysicists resort to the next best option to help understand the observed phenomena: computational simulation. The image in ***Fig. 2*** shows a rendering of a detailed simulation of the merger of two clusters, shown readily by the bright regions in the density (top left). The magnetic field strength is expected to look like the shown "blob", while an indicator of turbulence is shown in the bottom right. It is important for these simulations to understand exactly the interplay between the magnetic field and the dynamic, turbulent ICM.

Turbulence and Fields

The study of the evolution of a magnetic field containing turbulent plasma can be performed through computational simulations allowing for control and variation of a wide range of parameters governing the turbulence, plasma, and magnetic field. Our study focuses on the early evolutionary stages of the magnetic field, and how it is affected by turbulence. A detailed understanding of this relation is essential for accurate cosmological simulations and proper understanding of cluster phenomena. Our current general understanding is shown in ***Fig. 3.***

Magnetic Field Evolution

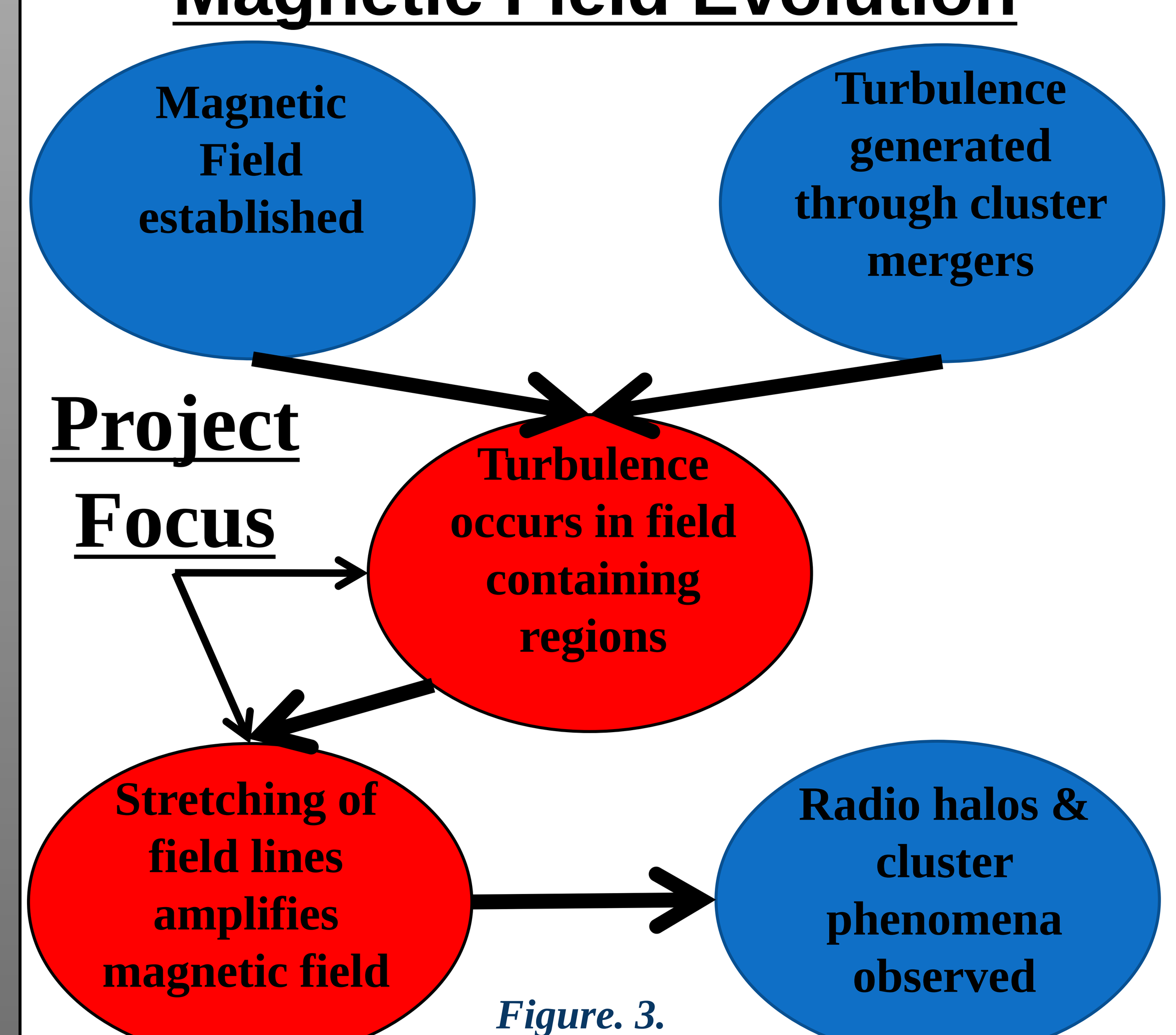


Figure. 3.

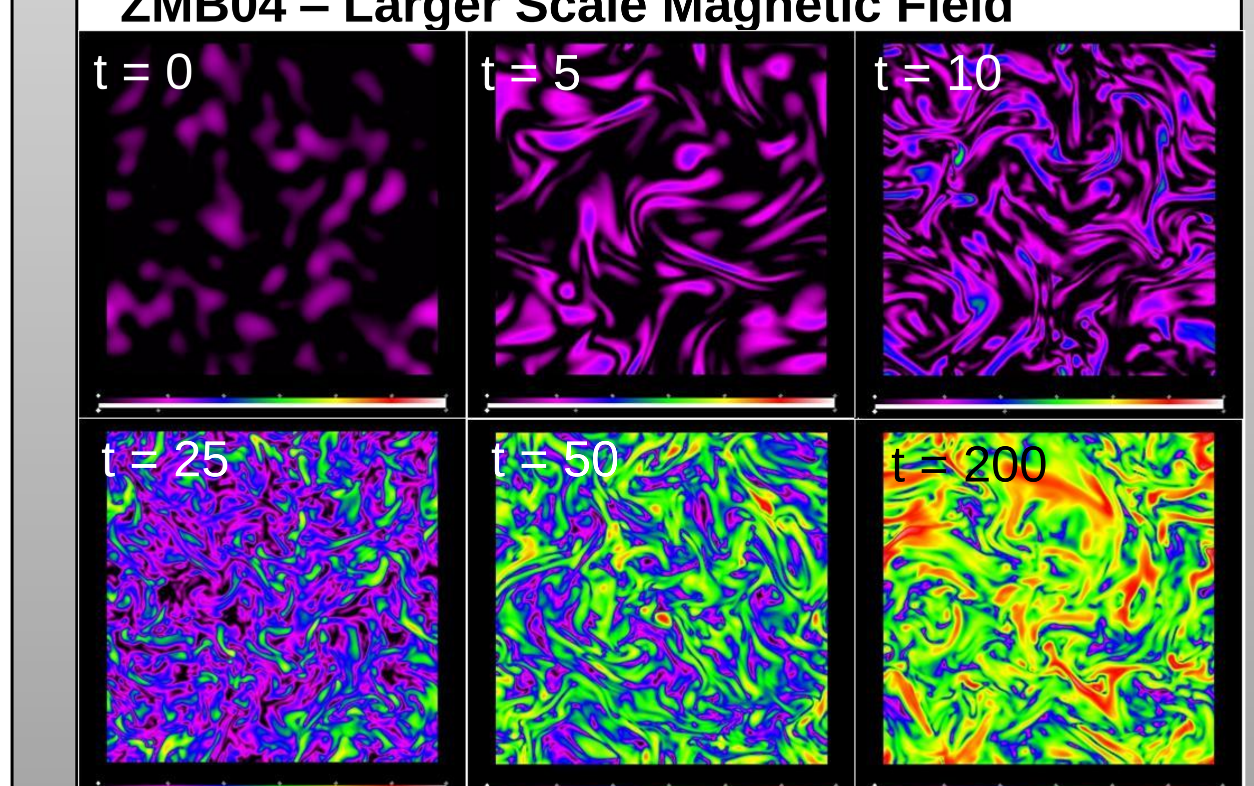
Magnetohydrodynamic Simulations

We have conducted six simulations of a plasma system driven by turbulent motions with varying initial magnetic field conditions. Outlined here are two simulations each containing an initial magnetic field that averages to zero across the system, called "zero mean background", or ZMB. The difference lies in the initial structures at which they are present, with ZMB06 originating in scales ½ that of ZMB04.

In turbulence, the field lines of the magnetic field are stretched and pulled. This stretching action increases the energy contained within the field and increases the strength of the field. This is the mechanism by which the field evolves.

Magnetic Field Strength

ZMB04 – Larger Scale Magnetic Field



ZMB06 – Smaller Scale Magnetic Field

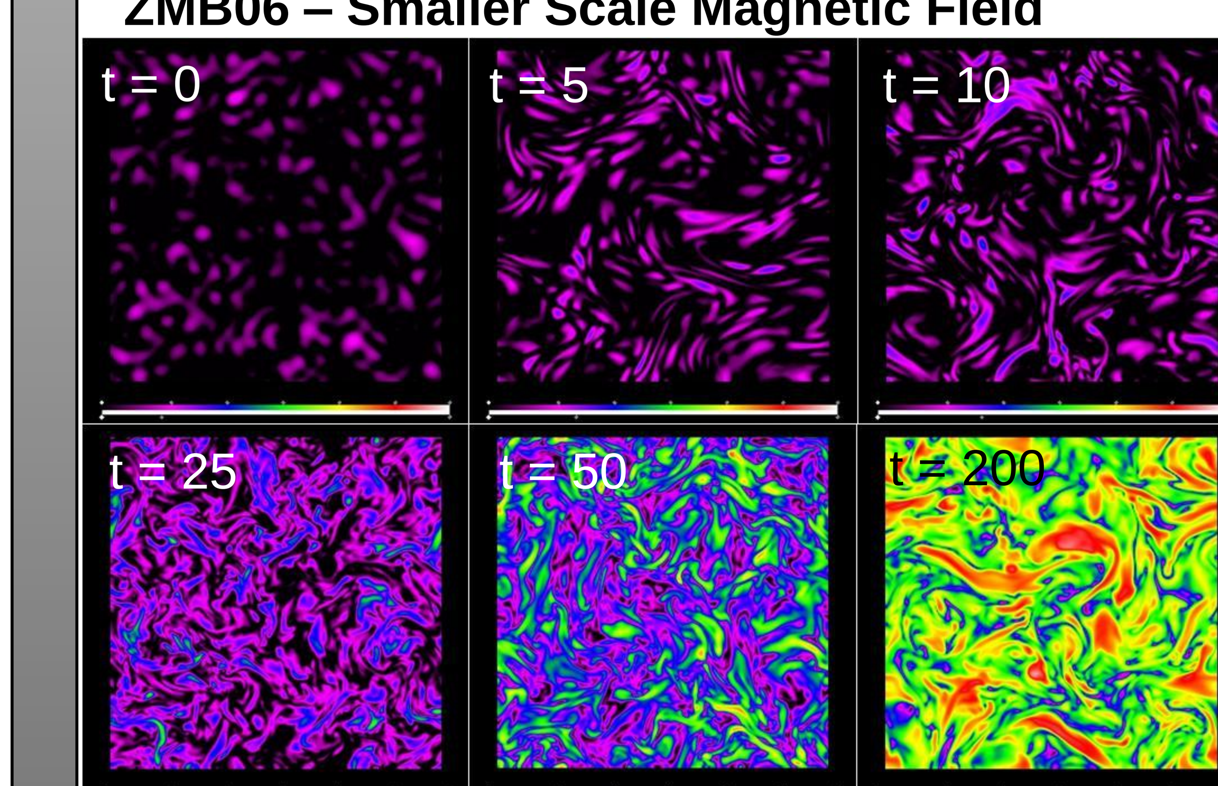
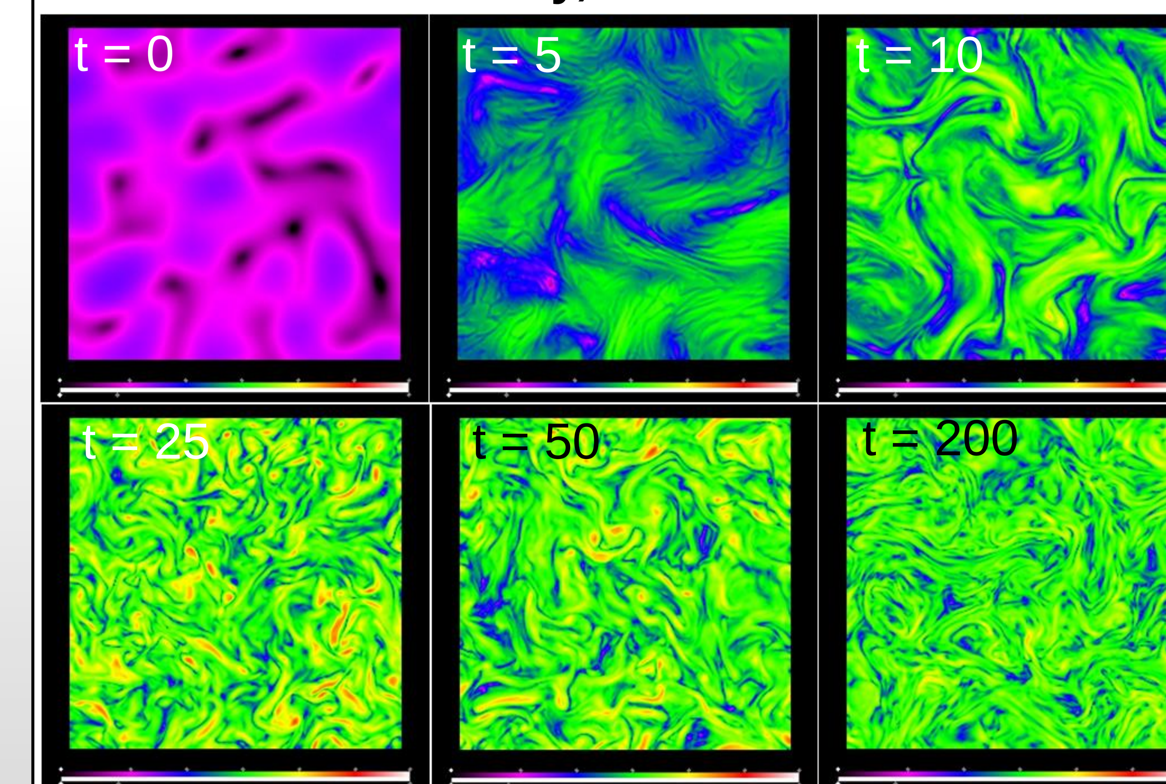


Figure. 4 Cross-sectional slices of the magnetic field strength showing significant changes during early and late evolution. Shown is ZMB04 and ZMB06 in the above two panels, with the turbulence for each in the panel towards the top right corner.

ZMB04/06 – Vorticity, Measure of Turbulence



Results and Conclusions

From the plots in ***Fig. 4***, there is a significant difference between the evolution of the two simulations. The scale structure of the initial magnetic field is important for its evolution. Below is a quick summary of results:

- More complex, twisting structures formed earlier in ZMB04, as the turbulence more quickly inputs energy into the magnetic field.
- Because of this, for ZMB04, field strength evolves roughly twice as fast as that in ZMB06.
- Regardless of initial structure, simulations reach similar final equilibrium states (t=200 in ***Fig. 4***)

The early evolution of the magnetic fields here are most important, and most applicable to the current observed state of galaxy clusters. With further work, the results of these and additional simulations will be directly applicable to the observed properties of cluster magnetic fields.

References:

Carilli, C. L., & Taylor, G. B., 2002, **ARAA**, 40, 319

Cho, J., & Vishniac, E.T., 2000, **ApJ**, 538, 217

Cho, J., et. al., 2009, **ApJ**, 693, 1449

Jones, T.W., et. al., 2008, **Mem. S.A.It.**, 75, 1

Acknowledgments

Support for this project was provided for by the Undergraduate Research Opportunities Program at the University of Minnesota (AE), the Minnesota Supercomputing Institute (TJ, DP), and the National Science Foundation (TJ). I would like to thank Dr. Tom Jones and Dr. Francesco Miniati for providing the cosmological simulation rendering in *Fig. 2*.

Further information

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