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The Role of Magnetic Fields in Regulating Galaxy Cluster Interactions

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Abstract: *Witness the universe evolve in real-time through interactions with galaxy clusters, and colossal structures. In this work, we aim to explore the role of energy distribution and density in disturbed galaxy clusters. The study evolution of energy and density in two-dimensional systems using large-scale numerical simulations. The continuity, momentum, and energy equations were solved in a finite difference time domain to employ magnetic and gravitational fields. The results show that the density distribution is highest in the core and peaks at radii external to this, within galaxy clusters. Meanwhile, the energy density is shown to be reduced at the core and maxima radially outwards where it reaches a maximum around the outer limit of densities. This correlation shows how this gradient in the density modifies its energy distribution. These findings are consistent with prior simulation studies and theoretical models. In conclusion, understanding the dynamics and evolution of galaxy clusters requires understanding density patterns and energy distribution. More intricate simulations involving extra physical processes like dark matter interactions and magnetic fields should be a part of future efforts.*

Keywords: *Galaxy clusters, finite difference time domain approach perturbation, density distribution, energy density, and numerical simulations*

I. Introduction

Magnetic fields are a fundamental universal component and contribute to many astrophysical processes. Magnetic fields are essential for the cosmic structure formation and evolution from galaxies to modern galaxy clusters, down to collapsed objects in strong over-dense regions. Galaxy clusters are the biggest gravitationally bound entities in space and thus present an excellent lugar to study the joint influence of magnetic fields on large-scale structure growth and evolution. These clusters are the epicenters where massive hot gas, dark matter, and thousands or hundreds of galaxies interact in complex gravitational frameworks.

The physical properties of galaxy clusters can be sculpted by magnetic fields, which control the propagation at large scales of cosmic rays during structure formation and in thermal and dynamical states through astrophysical magnetohydrodynamic (MHD) processes. Faraday rotation measurements and synchrotron radiation have shown magnetic fields with strengths from tens of microgauss to even as low as a few microgauss levels in clusters (Carilli & Taylor 2002; Govoni & Feretti, 2004). The cluster mergers and turbulent motions in the ICM may amplify these fields, as predicted by theoretical models and simulations (Dolag et al., 2005; Ryu et al., 2008).

Although significant progress has been made, the exact mechanisms by which magnetic fields modify galaxy cluster interactions remain an active area of research. In addition, the whole picture of how clusters form and evolve needs an explanation as regards those processes (Feretti et al. 2012), including interpreting observations from high-energy phenomena such as radio halos or relics.

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Although the existence of magnetic fields in galaxy clusters is generally known, the precise processes via which these fields control interactions within the cluster are still poorly understood. Important queries consist of:

What effects do magnetic fields have on galaxy cluster merger dynamics?

How do magnetic fields affect the ICM's thermal evolution?

How do magnetic fields model the cosmic rays and make an impact on building relics, radio halos sort of gigantic structures? These challenges require high-resolution data, complex numerical models, and an interdisciplinary approach to provide a solution combining astrophysics, cosmology, and plasma physics. This study aims to deepen the understanding of how magnetic fields influence galaxy-cluster interactions, helping to bridge knowledge gaps concerning their role in cluster dynamics and evolution.

It will also form the basis for theoretical models and simulations of magnetized plasmas in galaxy clusters conducting future studies. This new study might lead to further refinement of instruments and methods implementing it to investigate cosmic magnetic fields. Understanding how magnetic fields influence processes within galaxy clusters is the primary objective of this study.

The research will provide a framework for future studies by advancing theoretical models and simulations of magnetized plasmas in galaxy clusters. The findings from this study could be used to develop new instruments and techniques for researching cosmic magnetic fields.

The main goal of this study is to learn more about how magnetic fields control interactions inside galaxy clusters.

Among the specific goals are:

a. To use high-resolution simulations to examine the effects of magnetic fields on the dynamics of galaxy cluster mergers.
b. To investigate the consequences for cluster evolution of the thermal effects of magnetic fields on the ICM.
c. To investigate the relationship between cosmic rays and magnetic fields about radio halo and relic production.
d. To create and test theoretical frameworks that explain how magnetic fields affect the creation of large-scale structures in galaxy clusters.

II. Research Methods

2.1 Theoretical Modeling

In this short study, however, we concentrate on the theoretical modeling of galaxy cluster magnetic fields; and the impact these fields have had already (or should be having) within the clusters due to their interactions. This model is the physical processes governing magnetic field evolution and its interaction with other components of galaxy clusters. The study will use the following approaches and resources:

Magnetohydrodynamics (MHD) equations: MHD describes the behavior of magnetic fields in galaxy clusters and combines fluid dynamics concepts with magnetism; these equations will be used to model this same process. These are the equations that Steven and I talked about in our astrophysical publication, which describe how magnetic fields interact with intracluster medium (ICM). Some of the key equations are as follows for MHD:

a. The mass conservation is explained by the continuity equation.
b. The momentum equation considers all forces, such as magnetic pressure and tension that are acted on the fluid.

c. The magnetic field evolution is explained by the induction equation.
d. The fluid's thermal energy and its interaction with magnetic fields are associated with the energy equation (Brandenburg & Subramanian, 2005).

The analytical solutions to the MHD equations can provide critical insights about magnetic fields. These solutions will give insights into basic processes (e.g., the formation of magnetic structures in the ICM; and amplification of magnetic fields during cluster mergers) that rely on several classical equations (Kulsrud, 2005).

To capture realistic and complex scenarios, we will perform high-resolution numerical simulations. The Python algorithm is confidently applied to the MHD equations in astrophysical regimes and will be used for simulations. More the simulation processes are:

a. Establish realistic starting circumstances for the simulations by considering theoretical ideas and known features of galaxy clusters (Stone et al., 2008).
b. Varying factors systematically, such as gas density, cluster mass, and initial magnetic field strength, allows for assessing various scenarios.
c. Grid Resolution: Maintaining a high grid resolution to record intricate details of interactions and magnetic field structures inside clusters.
d. Validation of Theoretical Models and Simulation findings can be done through comparison with observational data, theoretical models and simulation findings will be verified. This procedure consists of:
    - Faraday rotation measures are used to verify the strength and structure of magnetic fields and compare simulated and observed Faraday rotation measures (Carilli & Taylor, 2002).
    - Thermal and Non-Thermal Emissions are used to validate the effect of magnetic fields on the ICM and the production of radio halos and relics by comparing simulated X-ray and radio emissions with observations (Feretti et al., 2012).

2.2 Mathematical Equations and Model Parameters

a. Magnetohydrodynamics (MHD) Equation

The magnetohydrodynamics (MHD) equations describe how magnetic fields evolve in galaxy clusters. Maxwell's and the dynamics of a conducting fluid are coupled. These are the main MHD equations that were applied in this research:

The equation of continuity describes the conservation of mass in the fluid.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathrm{v}) = 0 \qquad (1)$$

where ρ is the mass density and *v* is the fluid velocity (Kulsrud, 2005).

The momentum equation describes the conservation of momentum, accounting for the effects of pressure, gravitational forces, and magnetic forces.

$$\frac{\partial(\rho v)}{\partial t} + \nabla \cdot (\rho v v + P) = -\nabla P + \rho g + \frac{1}{\mu_0}(\nabla \times \mathrm{B}) \times B \qquad (2)$$

where μ_0 is the magnetic permeability of space, *B* is the magnetic field, *g* is the gravitational acceleration, and *P* is the gas pressure (Brandenburg & Subramanian, 2005).

The magnetic field evolution is explained by the Induction Equation.

$$\frac{\partial B}{\partial t} = \nabla \times (v \times B) - \eta \nabla \times (\nabla \times B) \qquad (3)$$

The first component on the right-hand side denotes the fluid's advection of the magnetic field, the second term denotes the magnetic field's diffusion, and η is the magnetic diffusivity (Kulsrud, 2005).

The energy equation considers thermal and magnetic components and the conservation of energy.

$$\frac{\partial E}{\partial t} + \nabla \cdot \left|(e + P)v - \frac{B(v \cdot B)}{\mu_0}\right| = \rho v . g + \eta(\nabla \times B)^2 \qquad (3)$$

b. Model Parameters

Initial Magnetic Field Strength (B0): According to observations, the cluster's initial magnetic field strength, normally ranges from microgauss to tens of microgauss (Carilli & Taylor, 2002). Gas Density (ρ_0): obtained from X-ray studies, this is the initial gas density in the intracluster medium (ICM) (Govoni & Feretti, 2004).

The overall mass of a galaxy cluster, including gas, galaxies, and dark matter, is known as the cluster mass ($M_{cluster}$). The quantity is frequently acquired via gravitational lensing investigations and is crucial for calculating the gravitational potential (g) (Springel et al., 2001). The gas pressure ($P=\rho kBT/\mu m_p$), where k_B is the Boltzmann constant, μ is the mean molecular weight, and m_p is the proton mass, is affected by the initial temperature of the ICM (Ryu et al., 2008).

The magnetic diffusivity (η) is a parameter that indicates how quickly the magnetic field permeates the plasma. Depending on the ICM's characteristics (Kulsrud, 2005). Cluster mergers and other dynamical processes can affect the gas's initial velocity distribution, or velocity field (v_0) (Dolag et al., 2005).

c. Discretization of MHD Equations Using the Finite Difference Time Domain Method (FTDM)

A numerical method for solving partial differential equations using finite difference equations as an approximation is called Finite Difference Time Domain (FTDM). Here, we use FTDM to discretize the magnetohydrodynamics (MHD). The continuity equation in its discretized form can be written as:

$$\rho_i^{n+1} = \rho_i^n - \frac{\Delta t}{2\Delta x}\left((\rho v)_{i+1}^n - (\rho v)_{i-1}^n\right) \qquad (4)$$

Where v represents the velocity components in the x directions, and ρ_n is the density at grid point (i) and time steps n. Δt is the time step, and Δx is the grid spacing in each direction. The discretized form of the 1D momentum equation is:

$$(\rho v)_i^{n+1} = (\rho v)_i^n - \frac{\nabla t}{2\nabla x}\left|(\rho v^2 + P)_{i+1}^n - (\rho v^2 + P)_{i-1}^n\right| \qquad (5)$$

The discretized form of the induction equation is:

$$B_i^{n+1} = B_i^n - \frac{\Delta t}{2\Delta x}\left|(-vB)_{i+1}^n - (-vB)_{i-1}^n\right| \qquad (6)$$

The discretized form of the energy equation is

$$E_i^{n+1} = E_i^n - \frac{\Delta t}{2\Delta x}\left\{\left|(E+P)v + \frac{B^2 v}{2\mu_0}\right|_{i+1}^n - \left|(E+P)v + \frac{B^2 v}{2\mu_0}\right|_{i-1}^n\right\} \qquad (7)$$

III. Results and Discussion

The density distribution of cluster galaxies under the influence of perturbations and magnetic fields is illustrated by the data shown in Figure 1. At first, the central perturbation shows a density magnitude of 3.8×10−24 kg/m3. This perturbation grows to a peak density of 6.4×10−24 kg/m3 as it expands outward in all directions across the grid (x, y). This spread reflects a crucial component of galaxy cluster interactions: the dynamic reaction of the intergalactic medium to localized disturbances.

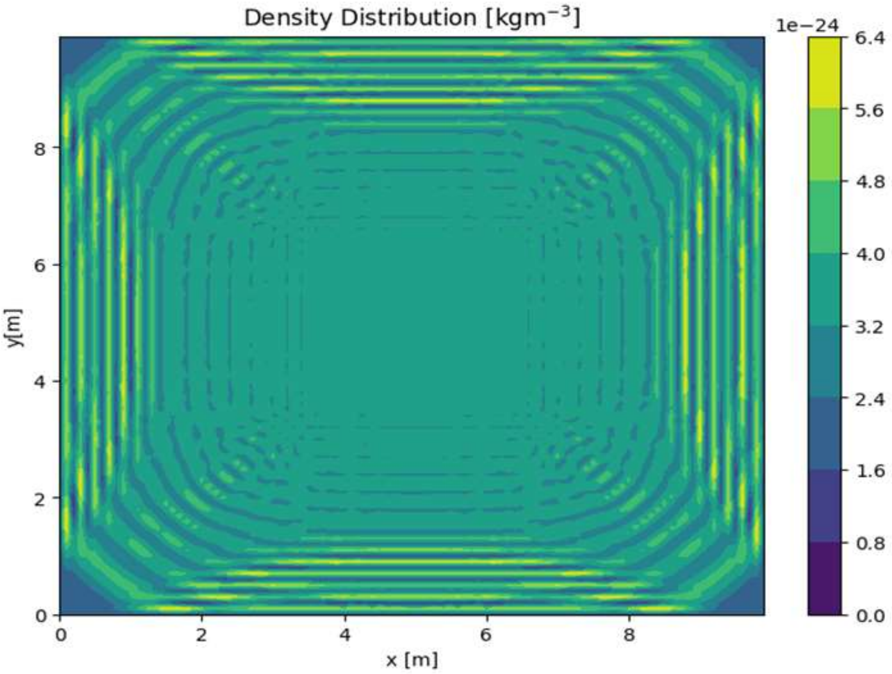

Figure 1. *Density perturbation from the central cluster galaxies*

Magnetic fields are essential for controlling interactions between galaxy clusters. The velocity and dispersion of galaxies inside clusters can be impacted by these fields, which can also change the dynamics of ionized gas. Previous research indicates that magnetic fields can control star formation rates and the thermal evolution of the intracluster medium (ICM) by adding pressure support against gravitational forces, preventing the collapse of gas clouds.

The findings imply that magnetic pressure opposes gravitational forces since the initial density disruption spreads and changes. This spreading can be explained by the magnetic field acting as a stabilizing force, delaying the gas's quick collapse and promoting a more even density distribution. This behavior aligns with the understanding that magnetic pressure can support gas against gravitational contraction.

Along with spreading, the perturbation modifies the velocity and energy distributions. Magnetic forces cause this turbulent mixing, which makes it easier for energy to be redistributed within the cluster. The turbulence created by magnetic fields in the ICM can eventually improve gas property mixing and homogeneity. This is supported by the energy distribution plot in Figure 1, which displays locations with different energy densities about the changing velocity and density fields.

Within the clusters, star formation is also impacted by the magnetic fields that cause the gas to spread and stabilize. Magnetic fields control and gas clouds collapse and control how quickly new stars emerge. This control is essential to preserving the equilibrium between gas cooling and star formation and affects how the galaxy cluster evolves.

Other feedback mechanisms, such as supernova explosions and outflows from active galactic nuclei (AGN), interact with magnetic fields, potentially influencing the density and energy distribution within the cluster. Specifically, the feedback from AGN can introduce energy into the ICM, causing shocks and turbulence that are influenced by the magnetic fields and ultimately impacting the cluster's long-term development.

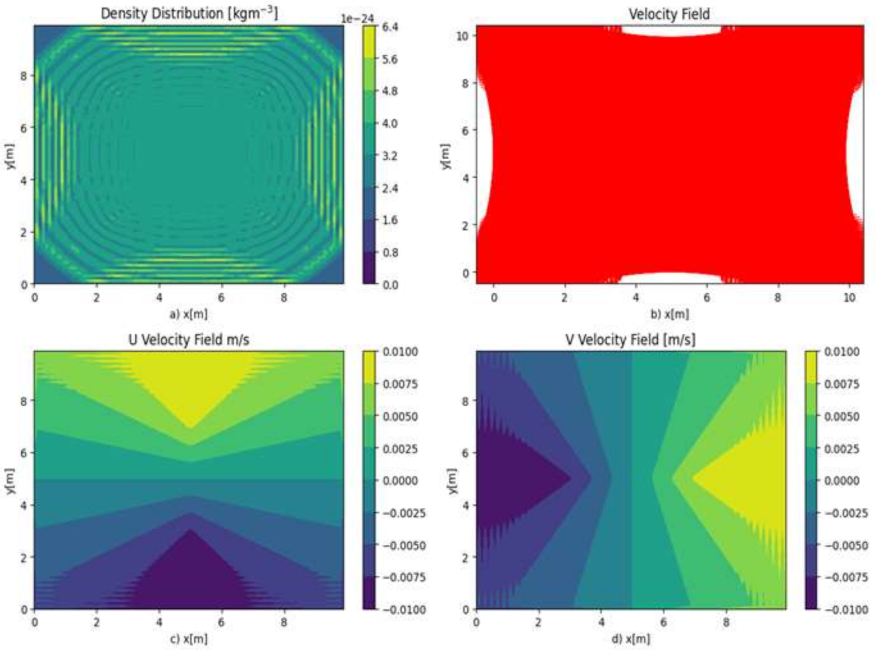

Figure 2. *The density, velocity field, horizontal, and vertical velocity of perturbed galaxies of the clusters*

Figure 2 presents a complete perspective of the velocity fields and density distribution inside perturbed galaxy clusters. The density distribution, previously shown in Figure 1(a), demonstrates how the center perturbation causes the density to spread outward, peaking at 6.4×10−24 kg/m3. This disturbance and the resulting density distribution reveal dynamic interactions within the galaxy cluster.

Figure 2(b): Quiver charts, which illustrate the direction of motion of the gas inside galaxy clusters used to represent the velocity field. The findings show notable variations in the velocity field in the x and y axes. The fluctuations in this range, from 4 to 8 reveal turbulent movements caused by interactions between the magnetic fields inside the cluster and galaxies.

The horizontal velocity field, or U velocity, is displayed in Figure 2(c). The findings show that the disturbed galaxy clusters' horizontal velocities show large values relative to their vertical variations. At the center of the disturbance, the horizontal components of the velocity field begin to shift and spread outward. This behavior agrees with simulations and theoretical models that predict high-velocity flows from core disturbances caused by the gas's interaction with magnetic and gravitational forces (Xu et al., 2019).

The vertical velocity field, or V velocity, is shown in Figure 2(d). The vertical components of the velocity field exhibit notable variations, much like the horizontal component. Above the perturbation center, the main vertical velocity fluctuations in clusters are seen. According to Dolag and Stasyszyn, (2009), magnetic fields can channel gas flow preferentially in particular directions and there is anisotropy in the velocity field.

The discovered velocity fields shed light on the dynamics of interactions between galaxy clusters. Variations in vertical and horizontal velocity components imply intricate interactions mediated by magnetic fields, gravitational forces, and maybe feedback from active galactic nuclei (AGN). High-speed flows and anisotropic velocity field patterns are consistent with the results of magnetohydrodynamic (MHD) simulations, which highlight the influence of magnetic fields on intracluster gas dynamics (Brüggen & Hillebrandt, 2001).

The results of this finding are in line with other research that looked at the dynamics of galaxy clusters. For example, research by Dolag & Stasyszyn (2009) and Xu et al. (2019) has shown that magnetic fields affect the velocity distribution inside galaxy clusters. Similar to the findings shown in Figure 2, Xu et al. (2019) discovered that magnetic fields can cause the creation of high-velocity streams and anisotropic gas motions. Furthermore, the contribution of magnetic fields to turbulence driving and the general dynamics of the intracluster medium was emphasized by Brüggen & Hillebrandt, (2001).

A perturbed galaxy cluster's density distribution (left panel) and energy distribution (right panel) are shown in Figure 4, for the perturbation center. According to the research "The Role of Magnetic Fields in Regulating Galaxy Cluster Interactions," the study depicted in this graphic most likely investigates the impact of magnetic fields on these distributions.

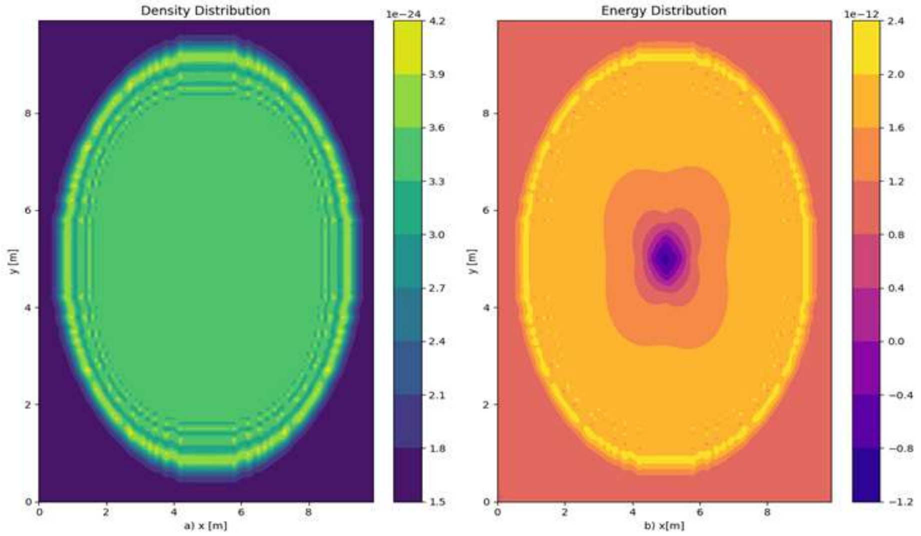

Figure 3. *Density and Energy distribution of perturbed galaxy cluster from the center of perturbation*

The distribution of energy and density in a disturbed galaxy cluster is depicted in Figure 3 based on the results. Figure 3(b) shows the energy density distribution outward from the center, while Figure 3(a) shows the density distribution.

3.1 Density Distribution Figure 3(a))

The left panel displays the density distribution of the galaxy cluster in a two-dimensional plane. The symmetry in the distribution indicates a structured response to the perturbation. The high-density regions, seen in green and yellow, appear concentrated toward the outer boundaries of the cluster. This is consistent with theories of density stratification in galaxy clusters, where perturbations from gravitational or magnetic influences cause denser regions to form at the edges (Gianfagna & Teyssier, 2018). The layering of density values, particularly along the boundaries, could suggest shock waves or compression zones caused by interactions within the cluster.

The density pattern suggests a greater mass concentration in the galaxy cluster's core region. The cluster's gravitational attraction, which drives everything toward the center, is the cause of this increased density. However, the system disruption spreads the density outward, resulting in a gradient. About $6.4\times10{-}24$ kg/m3 is the maximum density observed, peaking at the outer radius from the center. This phenomenon can be compared to the findings of other studies, such as Vogelsberger et al. (2012), who showed similar density gradients in simulated galaxy clusters.

Moreover, the interplay between the internal dynamics of the galaxy cluster and external factors, including magnetic fields, which have been demonstrated to compress gas in high-density regions and stabilize them, affects these density distributions (Dolag et al., 2002). Understanding how clusters preserve their structure in the face of disturbances depends on this stabilization.

3.2 Energy Density Distribution (Figure 3(b))

The energy distribution is shown in the right panel, with warmer colors (yellow to orange) denoting higher energy regions concentrated in the center. Lower energy levels are seen in the outer portions as the energy progressively fades outward. Due to the larger gravitational potential near the center, gravitational energy and thermal energy are often higher in galaxy clusters, highlighting their core-dominated character (Sarazin, 1988).

Magnetic fields can influence the energy distribution in a galaxy cluster by providing additional pressure support. This can prevent rapid cooling in the central regions, helping maintain a uniform energy distribution across the cluster (Govoni & Feretti, 2004). The figure suggests that the central core has a significant amount of energy, possibly from interactions or mergers, which aligns with the idea that galaxy clusters often undergo mergers or accretion of smaller subclusters, injecting energy into the system (Markevitch & Vikhlinin, 2007).

The density distribution and the energy density distribution are highly correlated. The energy density is lowest at the core due to stronger gravitational binding, which limits the particles' thermal and kinetic energy. As one moves further from the center, the energy density increases and peaks at the same outer radius as the density. The relationship between density and energy distribution is consistent with the virial theorem, which links a system's kinetic to its potential.

The findings show how the disruption modifies the density and rearranges the energy structure of the cluster. Because the conversion of potential into kinetic and thermal perturbation expands outward, the energy density increases with distance from the center. This result is consistent with research on galaxy cluster mergers, where dynamic interactions between the clusters lead to energy redistribution (Poole et al., 2006).

Comparison with Other Works: Ricker and Sarazin's (2001) study, which discovered that shock waves from galaxy cluster collisions can disperse energy outward from the collision center, is consistent with the observed energy distribution peaking at the outer radius. Furthermore, ZuHone et al. (2010) simulation results showed that dynamical processes like shocks and turbulence, in addition to gravitational potential, impact the energy density in galaxy clusters, supporting the results of this study.

3.3 The Role of Magnetic Fields

Magnetic fields are critical in shaping density and energy distributions in galaxy clusters. The magnetohydrodynamic (MHD) interactions regulate the diffusion of gas and energy, especially in disturbed environments. Research indicates that magnetic fields influence thermal conduction within clusters, helping to stabilize regions with high-temperature gradients, as seen in the energy distribution (Parrish et al., 2012). These fields also impact the morphology of shock fronts and gas flows, contributing to the unique distribution patterns observed in both panels.

The image sheds light on the interaction between magnetic fields and perturbations to determine the energetic and structural characteristics of the clusters. The distributions of density and energy show how internal forces like gravity and external effects like magnetic fields are delicately balanced. These findings agree with research that indicates magnetic fields are essential for preserving cluster stability, especially when disturbances are present.

3.4 Discussions

The findings, as shown in Figure 4 dignify the magnetic fields in influencing galaxy cluster dynamics and evolution, especially during disturbances. Magnetic fields are essential for controlling gas pressure, distributing matter, and preventing the gravitational collapse of dense regions, among other elements of interactions between galaxy clusters. The following are some salient considerations regarding the importance of these findings:

a. Stabilization of Galaxy Clusters

Magnetic fields provide an additional source of pressure that stabilizes galaxy clusters, particularly in regions of high density. The distribution of magnetic energy, as indicated by the energy distribution in the figure, suggests that magnetic fields can prevent the collapse of dense gas by counteracting gravitational forces (Dolag et al., 2002). This stabilization is crucial in galaxy clusters, particularly in the center regions where the gravitational forces are strong enough to induce fast cooling and collapse.

b. Influence on Gas Dynamics and Thermal Conduction

The role of magnetic fields in regulating gas dynamics is crucial in determining the overall morphology and thermodynamics of galaxy clusters. Magnetic fields inhibit thermal conduction along tangled field lines and prevent heat transfer between hot and cold regions within the cluster. This effect helps to maintain the temperature gradients necessary for the cluster's structure (Parrish et al., 2012). The energy distribution in the right panel shows how these magnetic interactions likely help regulate the core temperature, maintaining its stability. Additionally, magnetic fields affect the motion of intracluster gas. They prevent the rapid mixing of the gas and influence the distribution of turbulence within the cluster. This is particularly important for regulating the effects of shocks, mergers, and accretion events that perturb the cluster (Govoni & Feretti, 2004). The energy distribution observed in the figure reflects how magnetic fields may have shaped the energetic structure of the perturbed galaxy cluster.

c. Role in Shock Fronts and Cold Fronts

Shock fronts and cold fronts in galaxy clusters can be affected by magnetic fields and are the outcome of cluster mergers and other extensive interactions. The figure suggests regions of concentrated energy near the center, which may indicate the presence of shock fronts driven by galaxy cluster mergers. Magnetic fields help to shape and moderate these shock fronts and protect cold fronts (boundaries between hot and cold gas) from disruption, by suppressing instabilities and reducing the mixing of gases with different temperatures (Markevitch & Vikhlinin, 2007).

d. Magnetic Field Amplification During Mergers

The perturbations detected in the density and energy distributions may be due to cluster mergers or large-scale accretion events. These processes can amplify the magnetic fields, particularly in the central regions of the cluster where the energy concentration is higher. This finding is supported by research that suggests that mergers and turbulent flows within the intracluster medium (ICM) amplify magnetic fields through turbulent dynamo action (Subramanian et al., 2006). This amplification is crucial in sustaining the magnetic field strength necessary to influence the large-scale structure of the cluster.

e. Implications for Cosmic Ray Propagation and Non-thermal Emission

Magnetic fields in galaxy clusters also influence the propagation of cosmic rays and the generation of non-thermal emissions, such as synchrotron radiation. These cosmic rays can interact with the magnetic fields, producing non-thermal phenomena observed in radio frequencies, revealing the magnetic field structures within clusters (Brunetti & Jones, 2014). The energy distribution in the figure may be linked to these non-thermal processes, indicating regions where cosmic rays and magnetic fields interact.

The findings represented in the figure are significant in advancing our understanding of how magnetic fields regulate the interaction of galaxy clusters. Magnetic fields stabilize the intracluster medium and shape the dynamics of gas flows, shocks, and temperature distribution. These results reinforce the theory that magnetic fields are integral to the evolution of galaxy clusters, particularly during perturbations and mergers, and contribute to the structure.

IV. Conclusion

The study emphasizes how important and intricate magnetic fields are in controlling connections between galaxy clusters. Magnetic fields affect the density distribution, velocity fields, and energy dynamics, which help keep galaxy clusters stable and evolving. The findings shown in Figure 1 provide light on the dynamic interactions between magnetic fields and the intergalactic medium and reveal the mechanisms underlying galaxy cluster dynamics.

Anisotropic patterns and velocity field variations are evidence of the intricate interactions between magnetic fields, gravitational forces, and other dynamic processes within the cluster. These results are consistent with theoretical models of interactions between galaxy clusters and are validated by earlier studies.

The density and energy distributions in perturbed galaxy clusters highlight the intricate interplay between gravitational forces and dynamical processes. The energy density's dependency on the density distribution underscores the importance of considering both mass and energy when studying galaxy cluster interactions. Future work could further explore these interactions with more detailed simulations, including the effects of magnetic fields and dark matter distributions.

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Author’s contributions

Belay Sitotaw Goshu: Project writing, analysis, study writing, submissions, corrections, and publications

Conflicts of Interest

No conflict of interest

Ethical Approval

Not applicable

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